DURA BUILD CARE PVT. LTD.
AN ISO 9001 : 2008 COMPANY

Ground Improvement Techniques – with a Focused Study on Stone Columns

Rudrabir Ghanti* & Abhijeet Kashliwal
Dept. of Civil Engineering, VIT University
**rudrabir.ghanti@yahoo.com*

Abstract

In this paper we have made an in-depth attempt to present a brief account of various ground improvement techniques and on proper scrutiny mentioned their various key issues. Further, we have pointed out how these methods lose their importance on practical grounds and how on other hand stone columns hold the upper hand in Indian context on economic and practical feasibility. In addition to these, we have made an elaborate technical discussion on stone columns with much emphasis on its bulging and settlement characteristics when reinforced and encapsulated with geo-grids. Finally, we have listed down the important conclusions of this study along with more ideas and suggestions.

1. Introduction

Definition: In simple words-GROUND IMPROVEMENT can be defined as "the process of enhancing the quality of soil." Ground improvement mainly refers to the improvement of soil layers but in some cases it also refers to the improvement of rock layers. The ground improvement techniques applied are tools used by the geotechnical engineer for "fixing" the problems of poor ground. When a poor ground existed at the project site, for instance, the early builder was faced with the following questions:

- Should the poor ground be removed and replaced with a more suitable material?
- Should the weak ground be bypassed laterally by changing the project's location or vertically by the use of deep foundations?
- Should the design of the facility (height, configuration, etc) be changed to reflect the ground's limitation?

These limitations could not withstand the test of time. Due to acute shortage of land, heavy loading structures, competitive design and speedy construction, the field of civil engineering witnessed the dawn of GROUND IMPROVEMENT TECHNIQUE**.** With the development of ground improvement, the new questions facing the current builders are:

- Should the problematic ground at the project site be fixed instead of bypassed?
- What are the critical issues that influence the successful application of a specific fixing tool?
- Which fixing tool should be used for improving the soil conditions?

In this paper we intend to discuss the various ground improvement techniques and the issues which affect feasibility in the current state of practice especially in a country like India where cheap labor, economy and availability of resources plays such a big role.

2. Details on Ground improvement techniques (GIT)

GROUND IMPROVEMENT TECHNIQUES are basically employed to

- To decrease settlement.
- To increase the bearing capacity.
- To improve the drainage conditions and environment control.
- To control the deformation and accelerate consolidation.
- To increase the stiffness.
- To increase resistance to liquefaction.

2.1 Classification of GIT's

The soil improvement methods mostly used in the current state of the practice can be divided into eight main categories :

- Densification
- Consolidation
- Weight reduction
- Reinforcement
- Chemical treatment
- Thermal stabilization
- Electrotreatment
- Biotechnical Stabilization

Ground Improvement by Densification

For loose granular soils at the surface, stabilization and densification is achieved by compaction with conventional rollers. Densification at depth is accomplished using the following methods

- Vibrocompaction
- Dynamic
- Compaction
- Blasting
- Compaction Grouting.

In vibrocompaction, loose granular soils are densified at depth by insertion of vibrating probes into the ground. Compaction is achieved by impact and vibration, with or without the use of a water jet or compressed air, and with or without the addition of granular material. Densification can be achieved to up to 30m in depth. In **dynamic compaction**, large weights are dropped repeatedly on the ground surface at a predetermined grid pattern. The high-energy impacts cause densification of the soil mass to depths from 3 to 8 m. The drop heights are usually 12 to 24 m and the drop points are several meters apart in a grid pattern.

Densification by **blasting** is accomplished by detonation of explosives buried in the loose soils. The shock waves generated by the blast breaks down the initial structure of the soil and creates a liquefaction condition that enables the soil particles to rearrange themselves in a denser packing.

In **compaction grouting**, a very stiff mortar grout is injected in the ground under relatively high pressure to densify loose soil formations. In general, the grout does not enter the soil pores, but remains in a homogeneous mass that displaces and compresses the surrounding soil. The grout mix consists of silty sand, cement, additives and water.

Ground Improvement by Consolidation

Consolidation both the strength and unit weight of the soil are increased and its hydraulic conductivity is reduced when it is consolidated.Unfortunately, this improvement is accompanied by a volume decrease and ground deformations for which the soils are preconsolidated under loads more than design loads.There are basically three methods of ground improvement. Preloading with or without vertical drains Electro-osmosis· Vacuum consolidation

Preloading is usually accomplished by placing surcharge fills. Controlled filling of tanks or lined ponds, electro-osmosis or vacuum consolidation are alternative means of preloading. To accelerate consolidation, vertical (sand or prefabricated wick) drains are often used with preloading. Consolidation by electro-osmosis is the same in many aspects as consolidation under externally applied stresses, except that the driving force for drainage is induced internally by an electric field. In vacuum consolidation, both liquid and gas (water and air) are extracted from the ground by suction induced by the creation of vacuum on the ground surface and assisted by a system of vertical and horizontal drains.

Ground Improvement by Weight Reduction

This method of ground improvement involves reduction of the weight applied to a soft compressible soil by the use of lightweight fill material like Wood fibers, Sawed lumber waste,

Shredded tire , Clam shells ,geofoam,etc. The overall benefits gained from the use of lightweight fill materials include reduced settlement, increase, slope stability and increased resistance to earthquake effect.

The lightweight materials are placed over the native soil in one of three ways:

spread in a loose form, then compacted

cut in block forms, then stacked according to a certain arrangement, or

pumped in a flowable liquid form

Ground Improvement by Reinforcement

The soil and its reinforcing elements act in combination to increase the shear strength of the soil mass, reduce its settlement under the load, and improve its resistance to liquefaction. Reinforcing the soil is usually accomplished by one of the following methods:

Mechanical stabilization

Soil nailing

Soil anchoring

Micro piles

Stone columns

Fiber reinforcement

In **mechanical stabilization**, the reinforcing elements such as metals,polymers,geotextiles are placed between layers of compacted soil. For construction of retaining walls or embankment slopes, the reinforcing elements are usually attached to facings that retain the compacted soil at the face and protect the reinforcing elements from weathering effects. The types of facing used include precast concrete panels, cast-in-place concrete, metallic plates or baskets, geosynthetic grids or sheets, timber,etc .

Soil Nailing is an in situ technique for reinforcing, stabilizing slopes and retaining excavations and deep cuts through the introduction of relatively small, closely spaced inclusions (usually steel bars) into a soil mass, the face of which is then locally stabilized. A zone of reinforced ground results that functions as a soil retention system.

Rock and soil anchors offer an economical solution to temporary or permanent stability or support problems. Designed to withstand lateral and uplift forces, these structural members are typically used with temporary, deep excavation support systems, as a part of permanent retaining walls, for dam stabilization or to resist wind-produced uplift forces**.**

Micropiles are small diameter piles(less than 300mm) installed vertically and are spaced closer than in conventional pile foundations and the loads are supported by a complex soil-pile structure analogous to reinforced concrete, where the ground represents the concrete and the micropiles correspond to the steel reinforcements. The micropiles are installed by drilling and grouting.

Although constructed using the same equipment and procedure as **vibrocompaction stone columns** function as reinforcement rather than densification. The presence of stone columns transforms the ground into a composite mass of granular cylinders with intervening native soil, providing a lower compressibility and a higher shear strength than those of the native soil alone.

The newest concept of earth reinforcement is a three-dimensional technique involving mixing of continuous **polymer fibers (yarn)** with granular soil to form a composite material capable of resisting tensile forces.

Ground Improvement by Chemical Treatment

Cement, lime, fly-ash, asphalt, silicate and others are used to stabilize weak soils. They generally bind the soil particles together, resulting in higher strength and lower compressibility. In lime stabilization, an ion exchange reduces the soil's plasticity and improves its workability.

The chemical treatment methods includes:

- Permeation grouting
- Jet grouting
- Deep soil mixing
- Lime columns

In **permeation grouting**, cement, lime, bentonite or chemical grouts (silicates, etc.) fill the voids in the soil, resulting essentially in increased strength and cohesion and reduced permeability, with no change in the volume or structure of the original ground. Microfine cement grout is the latest addition to permeation grouting.

Jet grouting uses high-pressure fluids, applied through a nozzle at the base of a drill pipe, to erode the soil particles and mix them with cement grout as the drill bit is rotated and withdrawn, forming hard, impervious columns. It is used mainly for excavation support, underpinning.

Soil Mixing, also known as the Deep Mixing Method, is the mechanical blending of the in situ soil with cementitious materials (reagent binder) using a hollow stem auger and paddle arrangement. The intent of the soil mixing program is to achieve improved character, generally a design compressive strength or shear strength and/or permeability.

The **lime columns** are suitable at best for stabilization of deep soft clay deposits.A pozzolanic reaction takes place between the lime and the clay minerals resulting in substantial increase in the strength and reduction in the plasticity of the nativematerial. The heat generated by hydration of the quicklime reduces the water content of the clayey soils, resulting in accelerated strength .

Ground Improvement by Thermal Stabilization

The thermal stabilization methods discussed in this paper are:

- Ground freezing
- Vitrification

Ground freezing is used to prevent groundwater seepage into excavations and to increase the shear strength of the soil. Two basic systems are usually followed in freezing: an open systemwhere the refrigerant (liquid nitrogen or carbon dioxide) is lost to the atmosphere after it has absorbed energy and vaporized, or a closed-circuit hydraulic system using a conventional mechanical plant and a circulating

In **vitrification**, the soil is electrically melted at very high temperatures using graphite electrodes.The inorganic portion of the soil typically breaks down into major oxide groups, such as silica and alumina. Upon cooling, these groups form glass and crystalline products with excellent environmental properties.

Ground Improvement by Electrotreatment

The electrotreatment methods used in environmental geotechnology includes:

- Electrokinetic remediation
- Electroheating
- Electrokineting fencing
- Bioelectrokinetic injection

The first method is used mainly for extraction of ionic contaminants such as heavy metals, and the second for removal of volatile and semivolatile compounds. The last two methods are used to stabilize the contaminants in situ. Electrokinetic remediation uses a direct electric current applied across a soil mass by a set of electrodes which desorbs ions from soil particles.

Ground Improvement by Biotechnical Stabilization

This new form of ground improvement uses live biological objects (vegetation) as reinforcing elements.It is used for stabilization of cut or fill slopes, or construction of earth-retaining structures on parkland and in environmentally-sensitive areas.

Following table shows the key issues to be addressed with each ground improvement techniques.

Ground improvement methods	Key issues/problems associated
1. Densification	the percent of fines in the soil, the ability of the soil to dissipate excess pore water pressure, the energy felt by the soil, the presence of boulders and phenomenon ageing.
2.Consolidation	stability during surcharge placement, clogging of vertical drains, maintenance of the vacuum.
3. Weight Reduction	placement of the lightweight material which may be dusty, its longevity and long-term performance
4.Reinforcement	the load transfer to the reinforcing elements, the failure surface of the reinforced soil mass, the strain compatibility between the soil and the reinforcement, the arrangement and durabilityof the reinforcing elements
5.Chemical Treatment	soil-grout compatibility and reactivity,operational parameters,column verticality,weathering effects.
6.Thermal Stabilisation	the degree of saturation of the soil, the rate of groundwater movement,the post thawing behavior,the heat transfer in the melted soil.
7.Electrotreatment	the soil's electrical conductivity,the ionic characterization of the contaminants, the impact on buried objects and utilities.
8.Biotechnical Stabilisation	the development of artificial cohesion in the ground, (b) the effects of evapotranspiration, and (c) the durability of the vegetation.

Why do we choose **"STONE COLUMN"** out of so many **"Ground Improvement Techniques"** available?

- ✓ They act as vertical drains accelerating the process of consolidation and reducing post construction settlement.
- ✓ They also mitigate the potential for liquefaction and damage by preventing preventing build up of high-pore pressure by drainage-path.
- ✓ They have negligible demerits (which can be easily overcome by suitable techniques-e.g. BULGING can be easily prevented by encapsulation of stone column with geomembranes).

Significance Of Stone-Columns in INDIA

- ➢ Method of installing stone column (RAMMING) does not require any skilled labor-any layman can do the job.
- ➢ Its installation is economically very feasible-no high cost is required to do the execution.
- ➢ India has significant deposits of soft clays (especially along the coastal regions).

3. Stone Columns

- ❖ What are basically stone columns??

STONE COLUMNS are vertical columns of compacted aggregate are formed through the soils to be improved. *These columns result in considerable vertical load carrying capacity and improved shear resistance in the soil mass.*

- ❖ What Soils are Suitable for installation of STONE COLUMNS?

Any soil type that does not respond to vibration alone is a candidate for stone columns. These soils include silty and clayey sands, silts, clays, and some layered soils where damping of vibrations occurs.

3.1 Installation methods of stone columns

Most widely used methods for installation of stone columns are:

- ➢ VIBRO-COMPACTION METHOD.
- ➢ RAMMING (INDEGENEOUS METHOD).

Detailed Description of these:

3.1.1 *Vibro-compaction method*

The two primary methods of Vibro Stone Column construction are:

Wet, Top Feed Method (Replacement and Displacement)

In this technique, jetting water is used to remove soft material, stabilize the probe hole, and ensure that the stone backfill reaches the tip of the vibrator. This is the most commonly used and most cost-efficient of the deep vibratory methods. However, handling of the spoil generated by the process may make this method more difficult to use on confined sites or in environmentally sensitive areas.

Dry, Bottom Feed Method (Displacement)

This technique uses the same vibrator probes as standard Vibro-Replacement Stone Columns, but with the addition of a hopper and supply tube to feed the stone backfill directly to the tip of the vibrator. Bottom Feed Vibro-Replacement is a completely dry operation where the vibrator remains in the ground during the construction process. The elimination of flushing water in turn eliminates the generation of spoil, extending the range of sites that can be treated. Treatment is possible up to a depth of 80 feet and is not inhibited by the presence of groundwater.

Benefits of this method:

The Vibro-Replacement Stone Column Process

- ✓ Reduces foundation settlement
- ✓ Increases bearing capacity
- ✓ Mitigates liquefaction potential
- ✓ Provides slope stabilization
- ✓ Permits shallow footing construction
- ✓ Prevents earthquake-induced lateral spreading.

3.1.2. Ramming :
Ramming is an indigenous method. It can described as the “METHOD IN WHICH DENSIFICATION OF SOIL MASS IS ACHIEVED MANUALLY WITHOUT ANY SKILLED LABOUR”
Methodology:
Here, by using helical auger, at first bore-hole is made. Then, granular chips (of 2-3 cms in dia) are injected into the bore-hole. Compaction is done with the help of light hammer weighing 125kgs and falling from a height of 750 cms. This is a step-by-step process in which compaction is carried out in layers. Above each layer, sand cushion(of 10cm) is employed to prevent crushing of stones.

Significance of RAMMING

This method holds great significance in the context of our country. The following points justify this statement:

- ✓ No skilled labor required. Hence INDIAN mass power can be properly made to use.
- ✓ No big initial investment required- it’s highly feasible economically.
- ✓ Easy to follow the steps, no qualification required.
- ✓ Lastly, this method got its birth in INDIA, so can be indigenously followed.

3.2 Failure Modes of Stone Columns

STONE COLUMNS: are either constructed as *END BEARING* on a firm stratum underlying the soil or as a *FLOATING COLUMN* with the tip embedded within the soft clay. However, the former is used in practice. To make the most optimum application of stone columns, we must understand the various failure mechanisms it can undergo. Four Basic Failure Modes of Stone Columns are:

- ➢ General shear failure.
- ➢ Local shear failure.
- ➢ Bulging failure.
- ➢ Failure by sliding.

The modes of failure of Stone Columns depend upon the following parameters:

- ➢ Type of Stone Column (End-bearing or Free Floating).
- ➢ Type of Loading on columns.
- ➢ Passive resistance of tributary clay.

The following pictorial representation illustrates the various modes of failure clearly:

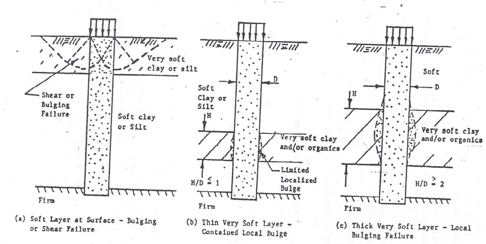


FIGURE 12. STONE COLUMN FAILURE MECHANISMS IN NONHOMOGENEOUS COHESIVE SOIL.

CASE-1: *Stone Column just loaded over the area of the column*

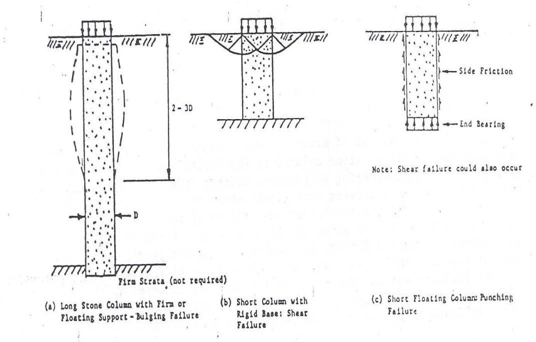


FIGURE 5. FAILURE MECHANISMS OF A SINGLE STONE COLUMN IN A HOMOGENEOUS SOFT LAYER.

CASE-2: *Stone Column loaded over an area greater than that of the column*

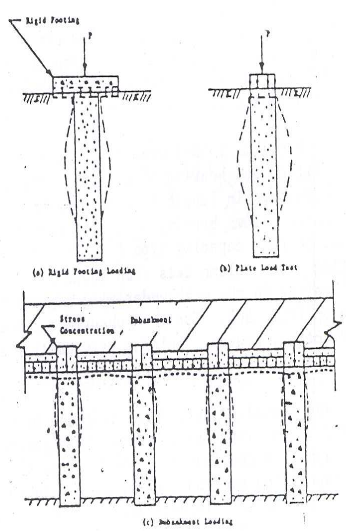


FIGURE 6. DIFFERENT TYPE LOADINGS APPLIED TO STONE COLUMNS.

NOTE: It is observed that "Applying load over an area greater than the stone column increases the lateral and vertical stress in the surrounding soft clay and also increases the ultimate load capacity"

ALTHOUGH, we discussed only the failure modes of SINGLE STONE COLUMNNS, SIMILAR concept can be extended to a group of columns. Nevertheless, it must be mentioned here that " Since the interior columns in a group are confined and somewhat stiffened by surrounding columns, the *ULTIMATE BEARING CAPACITY OF STONE COLUMN GROUPS* are greater than that of *SINGLE STONE COLUMNS*"

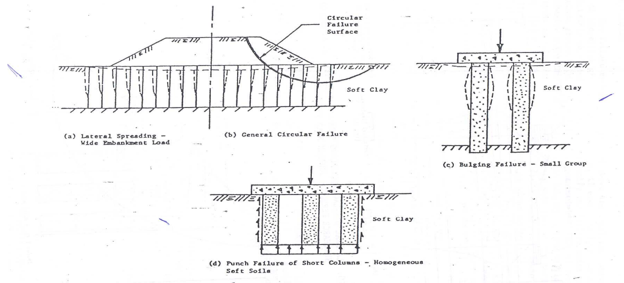


FIGURE 9. FAILURE MODES OF STONE COLUMN GROUPS.

Pictorial Representation Of Failure In Stone Column Groups

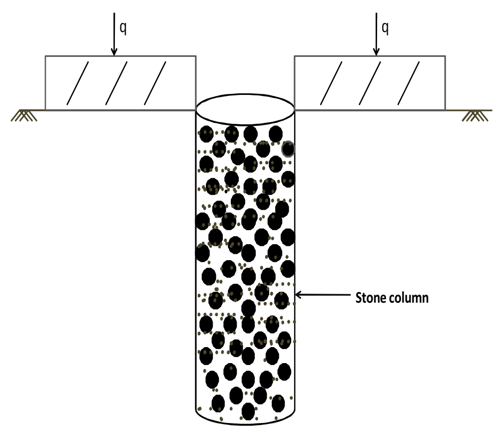
In practice, we find group of STONE COLUMNS (not a single pile) and that too of length greater than 3D-5D. Thus, In case of group piles "BULGING" is the primary mode of failure. Only, groups with short columns fail in end bearing (either local or general shear failure).

Keeping this practical aspect in mind, we discuss here the different methods to ARREST 'bulging':

3.3 **Methods to arrest bulging**

3.3.1.Placing of surcharge

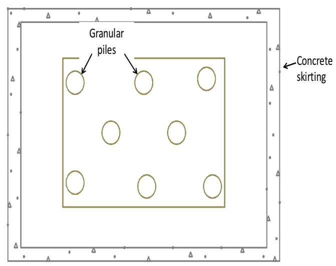
Placing of surcharge in the tributary of stone column increases the lateral passive resistance of clays- and hence the "ULTIMATE LOAD BEARING CAPACITY OF STONE COLUMN"



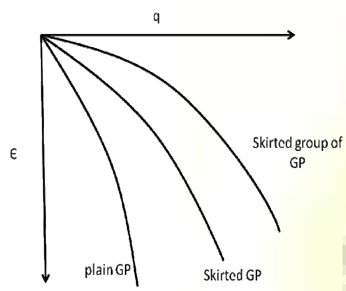
By placing surcharge on clay surrounding the stone column

3.3.2. Skirting

In this method, the bulged portion of pile is replaced by concrete plugs or cement grout. The concrete plugs increases the passive resistance of clays by considerable amount



Skirting for a group of granular piles



3.3.3 Geogrids And Geomembranes:

By reinforcing stone columns by GEOGRIDS or envolping it with geomembranes, the "ultimate bearing capacity of stone columns can be increased to considerable amount"

4. Ultimate Bearing Capacity of a Single Stone Column

By "ultimate bearing capacity" we mean that critical equilibrium when –*"the lateral stress developed in the stone column just exceeds the passive resistance of the surrounding clay"*. At failure, since the stone column throws itself into the surrounding clay- the Ultimate Bearing Capacity of Stone Column depends on the Clay in which the column has been injected. It must be mentioned here that- "If C_u < 30 kPa, we do not go for Granular Piles."

However, following are the different approaches of calculating the Ultimate Bearing Capacity of a Granular Pile:

4.1. Passive Pressure Approach*:*

In this approach (given by Greenwood), the pile dilates (bulges) into the surrounding clay and is resisted by the passive pressure of the surrounding clay. Hence, we can conclude-"*the Ultimate Strength of Surrounding Clay is equal to the lateral strength of the clay surrounding it.*"

Therefore, $q_u = p_p = k_p(\gamma z) + 2C_u\sqrt{(k_p)}$

Where,

(γ)- is the bulk density of the clay

Z – Is the total depth of bulge.

K_p- coefficient of passive Earth pressure.

4.2. Limit lateral stress approach*:*

In this approach {given by Schlosser, 1983}, the granular pile is considered as single incompressible, rigid plastic column contained in a semi-infinite plastic soft soil. The lateral stress is given by:

$\sigma_r = 2C_u + \sigma_s$

where,
σ_r – lateral limit stress.
C_u – undrained cohesion of clay.
σ_s – normal stress.

4.3.Cavity expansion approach

In this approach {given by VESIC, 1972}, he imagined the lateral bulging of the granular pile as "*an infinitely large cylinder expanding into the soil and the confining pressure inside the cavity is evaluated.*"

$\sigma_r = \sigma_3 + c[\,1 + \log_e \{E_c / (1 + \mu_c)\}\,]$.
σ_r = Ultimate lateral stress
σ_3 = Insitu lateral stress before expansion
c = cohesion of the clay
E_c = Young's Modulus of the clay
μ_c = poisson ratio of clay
$q_u = k_p\,\sigma_r$
$\sigma_1 / \sigma_3 = k_p = \{(1 + \sin\varphi_s) / (1 - \sin\varphi_s)\}$

4.4. Unit cell approach

Out of all the methods available, for predicting the "Ultimate Strength of a Stone Column", this approach has a high practical value. The reason is- in all the above mentioned approaches the "Ultimate Strength was found out for a single granular pile, but in practice we hardly find a single stone column". *This method, bears the specialty that it can extended to a group of stone columns.*

CONCEPT OF UNIT CELL:

Out of many possible patterns of packing { like square, rectangular, circular, triangular} the triangular pattern is usually employed because it gives the most dense packing of all { found experimentally}. The following figure illustrates this.

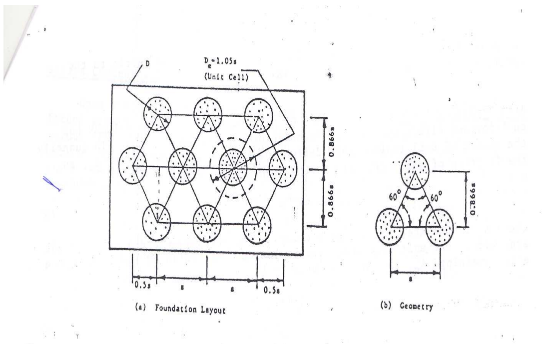


FIGURE 13. EQUILATERAL TRIANGULAR PATTERN OF STONE COLUMNS.

Here, as seen in figure although the tributary area forms the regular hexagon about the stone column but for all practical purposes it can be closely approximated to an equivalent circle having the same area with an effective diameter (D_e) of:

$$D_e = 1.05\ s$$

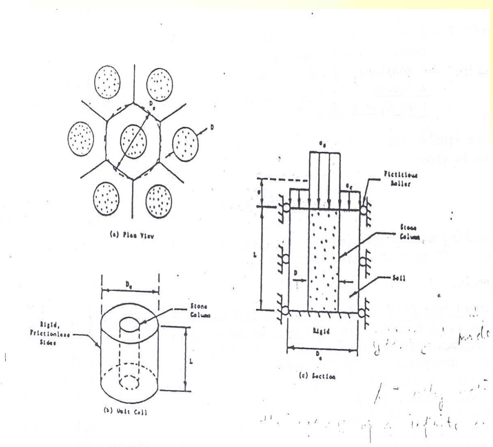


FIGURE 14. UNIT CELL IDEALIZATION.

Where "s" refers to spacing of stone columns

The resulting cylinder with diameter (D_e), enclosing the stone column and tributary clay is termed as a unit cell. As the vertical settlement of granular pile and the soil is approximately same, stress concentration occurs in the granular pile. The distribution of vertical stress is expressed by a stress concentration factor, n as

$$\eta = \delta(\sigma_s / \sigma_c)$$

where,

σ_s = stress mobilized in stone column material.

σ_c = stress in clay material.

Average stress (σ) at a given depth of unit cell is given as:

$$\sigma = \sigma_s (a_s) + \sigma_c (1 - a_s)$$

Where,

a_s = Area Replacement ratio = Area of stone column (A_s)/ Area of Unit cell (A_c).

Using this ratio, the stress in the stone column and tributary soil is calculated as:

$$\sigma_c = \{\sigma / (a_s (\eta - 1) + 1)\}.$$

$$\sigma_c = \mu_c (\sigma).$$

μc = stress coefficient in tributary clay.

AND,

$$\sigma_s = \{ (\eta\ \sigma) / ((\eta - 1)\ a_s + 1) \}$$

$$\sigma_s = \mu_s(\sigma)$$

μ_s = stress coefficient in stone column

NOTE: $\mu_s = \eta\ \mu_c$

5. **Experiment conducted on stone columns**

Laboratory scale model tests on soft clay beds reinforced with stone columns was performed wherein compressive load response of the composite ground was assessed. Plate load tests were being conducted on soft clay beds compacted to the predetermined density and water content (or consistency index) reinforced with stone columns prepared with different types of sand such as fine sand, medium sand and coarse sand. The relative density of granular material used were 40%, 50% and 60%. Consistency index(I_c) was varied for 60%,50%,40% where $I_c = (L_L - w_c) / (I_P)$.

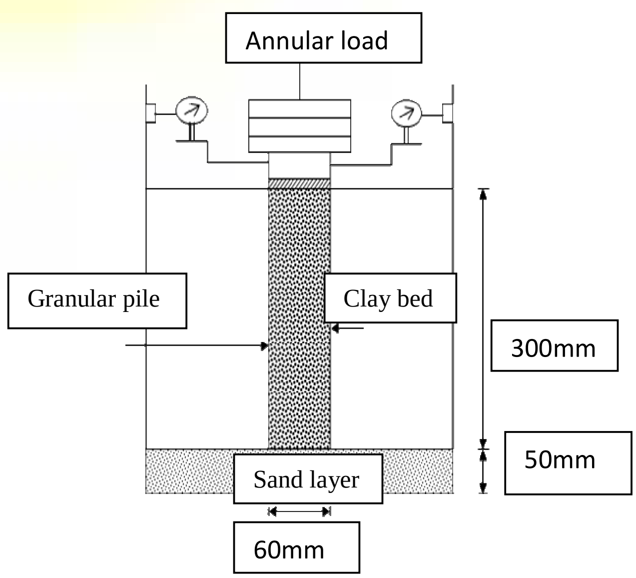


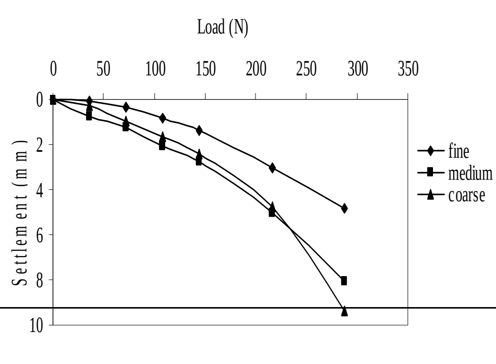
Table: Soil Parameters

Specific gravity	2.68
Liquid limit (%)	60
Plastic limit (%)	26
Plasticity index (%)	33
Compaction properties	
OMC (%)	21
MDD (kN/m^3)	16.6
USCS classification	CH

Table 1. Test Results from Experiments

Consistency	Type of sand	Max bulge dia (cm)	Max bulge length (cm)	Maximum settlement (cm) δ_{max}
60%	Fine	6.75	12	0.48
	Medium	6.9	14	0.81
	Coarse	7.3	18	0.94
50%	Fine	7.1	16	1.8
	Medium	7.2	16	2.6
	Coarse	8.65	18	6
40%	Fine	8.25	16	5.3
	Medium	8.8	16	6.5
	Coarse	9.8	14	10.8

It was found that the load bearing capacity for the fine sand was showing the best values ..



Geogrid reinforcement and encapsulation

It is a stiff or flexible polymer grid like sheets with large aperture used mainly for reinforcement of unstable soils.They can be stretched in both directions for improved properties. It is made up of high density polypropylene.We placed the geogrids at different layers and later encapsulated it and observed the results.

Out of the above tests conducted we have chosen 50% consistency index clay bed reinforced with coarse granular fill for improving the behaviour of the stone column.

Fig 1. shows the load-settlement curve for unreinforced and reinforced stone column with geogrids. With the introduction of geogrids it can be seen that settlement of the column decreases drastically. However, it can be also seen that stone column encapsulated as well as horizontally reinforced gave the best result.

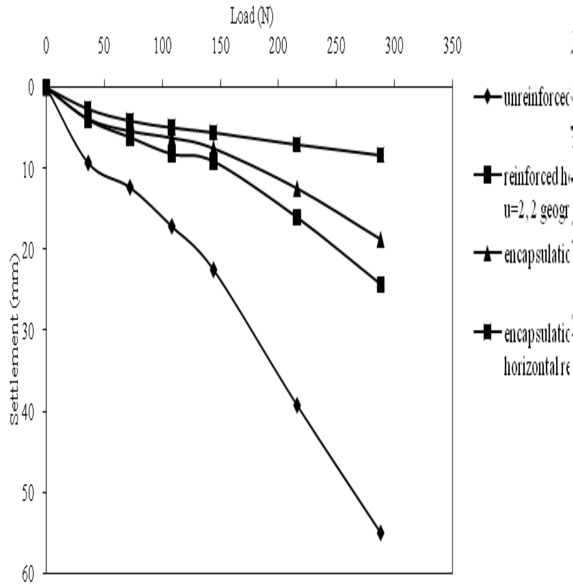
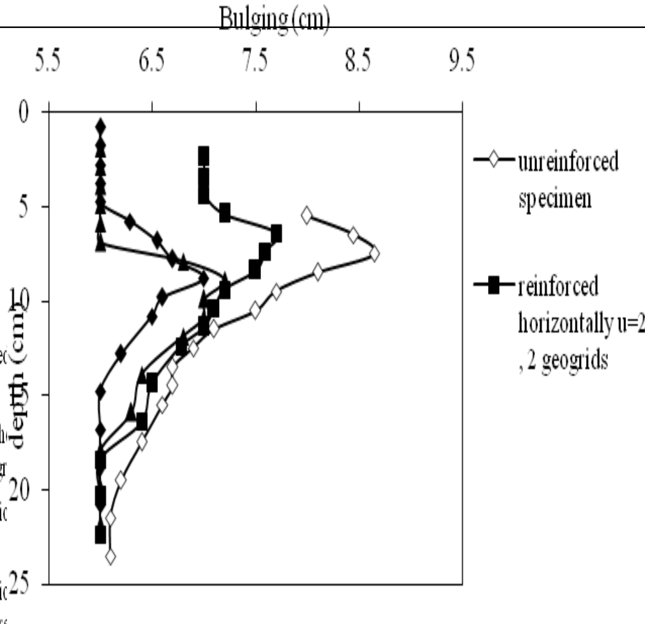


Fig 1. Load-settlement curve



Fig

Fig 2. shows the bulging profile of the unreinforced as well as reinforced stone column. Same trend as that of load settlement curve can be seen. Encapsulated stone column with horizontal geogrid gave the best result.

6. **Conclusions**

- ✓ Looking into the various technical aspects of installing and fixing STONE COLUMNS , we can vividly conclude that this technique is highly compatible and feasible for INDIA both economically and practically.
- ✓ Further, it has been observed that when the stone column was both encapsulated and horizontally reinforced the settlement and bulging reduced to a noticeable extent.
- ✓ The practical implications of STONE-COLUMNS are many. These include stiffening soil for tank foundations, highway-embankments, railway foundations, reinforced earth walls, individual footings, industrial structures, bridge- approaches and runways. This proves the versatility of this indigenous technique.

7. Ideas and Suggestions

- ➢ We must realize that “till date relatively very little is known about the interaction between STONE COLUMNS and surrounding soft clays”. Hence, more research and investigation needs to be done on this area to have the most optimum application of stone columns.
- ➢ Much importance needs be given on the installation technique of STONE COLUMNS or else its effective functioning would be hampered.
- ➢ It should be borne in mind that “just by analyzing results obtained from different GROUND IMPROVEMENT TECHNIQUES-we cannot conclude which is the best one”. The employment of a particular GIT, depends largely upon in-situ condition, quality of output that is desired, economic feasibility and design criteria. Based on these parameters, the most apt technique is chosen.
- ➢ Talking in context of INDIA, it has substantial amount of soft clays along the coastal regions. Moreover, owing to the economic feasibility and cheap labor, stone column technique of improving ground behavior can prove quite useful in INDIA, if executed properly.

8. References

1. Munfakh, G. A. (1997). “Ground improvement engineering – issues and selection.”

2. “Ground improvement techniques” by Dr.P.Purushothama Raj.

3. “Compressive load response of granular piles” by Dr.B.R.Phanikumar.

4. T. Ayadat and A.M. Hanna, Encapsulated stone columns as a soil improvement technique for collapsible soil, *Ground Improvement* 9 (2005) (4), pp. 137–147.

5. Geosynthetic encased stone columns: Numeric evaluation by S.Murugesan and K.Rajagopal (2006)
6. Sharma R.S. , Phanikumar B.R., and Nagendra(2004), Compressive Load- response of Geo-grid reinforced granular piles in soft clays, Canadian Geotechnical Journal,Volume-41, NO-1. Pp. 187-192.

Net search:

7. www.google.co.in
8. www.haywardsbaker.com