# "Study of Reinforced and Unreinforced Stone Column Behaviour For Ground Improvement"

## A PROJECT

***Submitted in partial fulfillment of the requirements for the award of the degree of***

**BACHELOR OF TECHNOLOGY**

**IN**

**CIVIL ENGINEERING**

**Under the supervision of**


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## Certificate

This is to certify that the work which is being presented in the project report titled **"Study of Reinforced And Unreinforced Stone Column Behaviour For Ground Improvement"** in partial fulfillment of the requirements for the award of the degree of Bachelor of Technology in Civil Engineering and submitted to the Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat is an authentic record of work carried out by Apurva Singh (141638), Rahul Mittal (141639) & Harshit Varshney (141649) during a period from January 2018 to May 2018 under the supervision of Dr. Saurabh Rawat, Assistant Professor, Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat.

The above statement made is correct to the best of our knowledge.

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## Abstract

Soil reinforcement techniques are common in use globally. One of these techniques is **Stone Columns**. Stone columns have proved to be effective for supporting structures built on loose soils. In this report, experiments on 3 types of stone columns have been done i.e**. Unreinforced** stone columns, **Vertically reinforced** stone columns and **Horizontally reinforced** stone columns installed in **sand**. The main goal behind this project is to study the effects of providing reinforcements of geosynthetics in the stone column (both vertically and horizontally) and the failure pattern of the stone columns in all 3 conditions.

The experiment was also done using **Finite Element Method**. Both the methods gave the same final results that the bearing capacity of the soil having reinforced columns in much more as compared to the bearing capacity of soil having unreinforced stone column. However, bearing capacity of horizontally reinforced stone column turned out to be slightly more than that of the vertically reinforced column. Also, failure pattern in all 3 cases turned out to be bulging.

# CHAPTER 1
# INTRODUCTION

## 1.1. General

This project studies the behavior of stone columns in improving the ground and its properties. This chapter deals with stone column as a ground improvement technique and their failure mechanisms. Stone columns can be installed by using the replacement method, displacement method or the rammed columns method. Reinforcements may be used to increase the strength of these columns. Different types of reinforcements and their possible placing has also been discussed. Suitability of stone columns varies with the type of ground. The numerical modeling using Plaxis 2D has also been introduced.

## 1.2. Stone Columns

Stone columns are a technique for ground improvement in soft soils for flexible structures which can bear some settlement, developed mainly in Europe. When such structures are loaded from the top, the columns deform laterally and settle into the soil. The failure occurs due to bulging of the column at its neck. The columns get their strength from mobilizing lateral earth pressure of the surrounding soil. In case of very soft soils, reinforcements need to be introduced in order to get the desired strength. It has been observed that reinforcement leads to higher reduction in volumetric strain of the loose specimen than that of the dense specimen. (Wu and Hong,2009) Research has also shown that the load carrying capacity of stone columns increased up to 3-5 times when it is reinforced. The bulging length of a reinforced column was studied to be reduced by up to 50% in comparison to an unreinforced stone column. Due to its low costs and versatility, this technique is used widely for an improved load carrying capacity, decreased settlement of foundations and hasten the consolidation settlements due to decrease in flow path lengths.

## 1.3. Methods of Ground Installation

A stone column may be constructed using aggregates or trampled rocks such that the particle size is <1/7th of the column diameter. General installation may be in the shape of a circle, triangle, square or hexagon. The installation techniques may be any one of the following:

### 1.3.1. Replacement Method

The in-situ soil should be relatively soft with a high ground water table. A vibroflot (vibratory probe) along with a water jet is used for creating holes in the soil which are then filled with stone column material.

### 1.3.2. Displacement Method

The method is used for firm soils and low water table levels. The natural soil is displaced laterally using compressed air dispensed from a vibroflot. The stone column is then installed in the void so created.

### 1.3.3. Rammed Columns Method (Case- Borehole Method)

Pre-bored holes are filled in stages by using heavy falling weights to ram the granular material into these holes.

After installing the columns, a sand blanket of 0.3m thick is placed on top to work as a drainage layer and to enable uniform stress distribution. (Shahu,2006)


**Fig. 1.1** Replacement Method for stone column installation ( Naik, 2013)


**Fig. 1.2** Displacement Method for stone column installation ( Naik, 2013)

## 1.4. Geosynthetic Material as a Reinforcement

ASTM defines geosynthetic as a planar product manufactured from a polymeric material used with soil, earth, or other geotechnical-related material as an integral part of a civil engineering project, structure or system. Geosynthetics can appreciably improve the safety factor, performance and cut down costs when compared with conventional designs and construction substitutes. They are used as a reinforcement material.

### 1.4.1. Types and manufacture

Synthetic Polymers, which are highly resistant to biological and chemical degradation, such as polypropylene, polyester, polyamide, PVC, etc are used for manufacture of most geosynthetics.

The geosynthetic materials maybe of the following types:

1. **Geotextiles**

Majorly used for providing separation, soil reinforcement, filtration of soil particles, drainage and an amalgamation of these functions. This project studies the use of geotextiles as reinforcement.

2. **Geogrids**

Used for uni-axial and bi-axial soil reinforcement, these geosynthetics are created by intersecting and joining of longitudinal and transverse rib sets giving open spaces known as *apertures*.

3. **Geonets**

Mainly plastic materials having uninterrupted ribs, arranged in a grid pattern, having openings smaller than geogrids.

4. **Geomembranes**

Geosynthetics having low permeability, which can be used as fluid barriers.

5. **Geocomposites**

They are a hybrid material formed by combining geosynthetic materials like geotextiles and geonets.

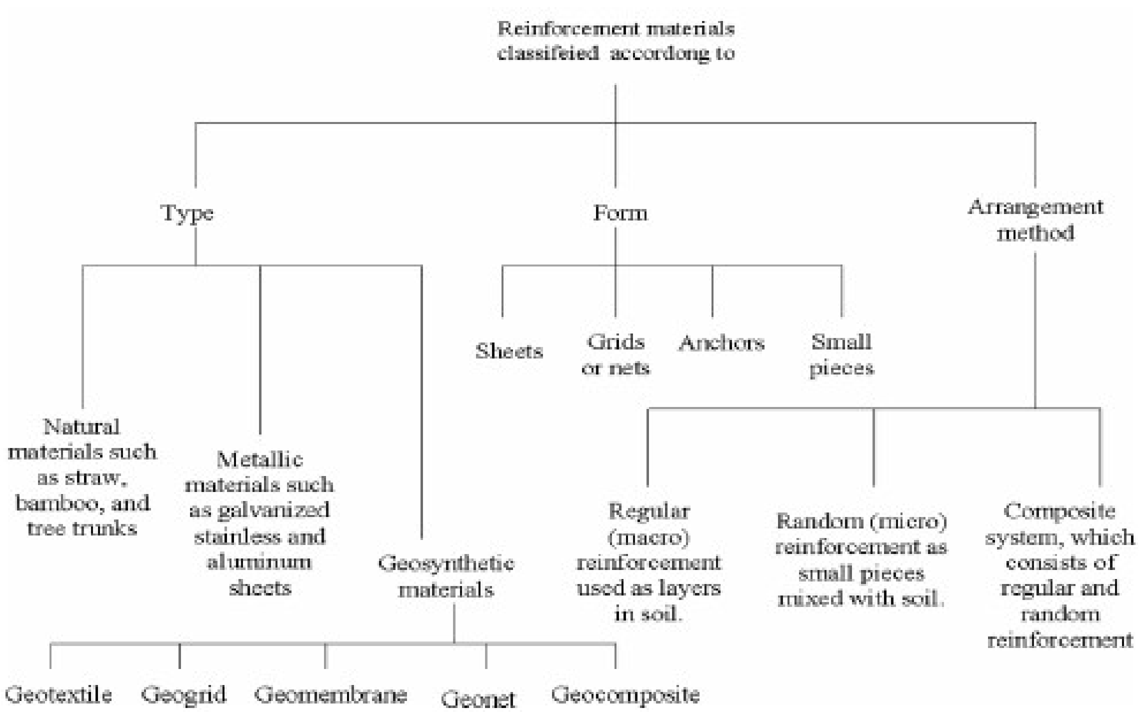



**Fig.1.3**Classification of Reinforcement materials (Elsawy, 2010)

### 1.4.2. Methods of Reinforcement

1. **Encasing the column in Geotextile**

Geotextile coating stabilizes the column through ring tension forces which depends on the column-geotextile interface. Hoop stress mobilization leads to the higher resistance against bulging obtained in this type of reinforcement.

2. **Placing horizontal geotextile discs at equal intervals along the column**

The bulging failure is prevented by mobilization of frictional stresses on the geosynthetic surface.

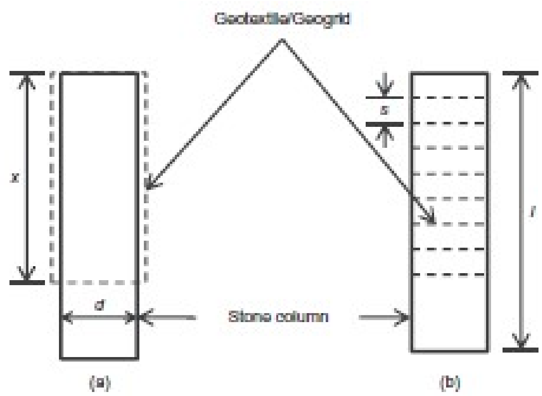



**Fig 1.4** Different reinforcement configuration

a) vertical encasement b)equidistant horizontal circular discs

## 1.5. Suitable soils for Stone Columns

The usefulness of stone columns in various soil types when using vibro-replacement technique are given below:

**Table 1.1** Suitability of stone columns in different soils (Naik, 2013)

| Ground type | Relative effectiveness | |
|---|---|---|
| | Densification | Reinforcement |
| sands | excellent | very good |
| silty sands | very good | very good |
| non plastic silts | good | excellent |
| clays | marginal | excellent |
| mine spoils | excellent depending on gradation | good |
| dumped fill | good | good |
| garbage | not applicable | not applicable |

## 1.6. Failure Mechanisms of Stone Columns

Single stone columns can fail by the following possible methods:

- Bulging Failure
- Pile Failure
- General Shear Failure

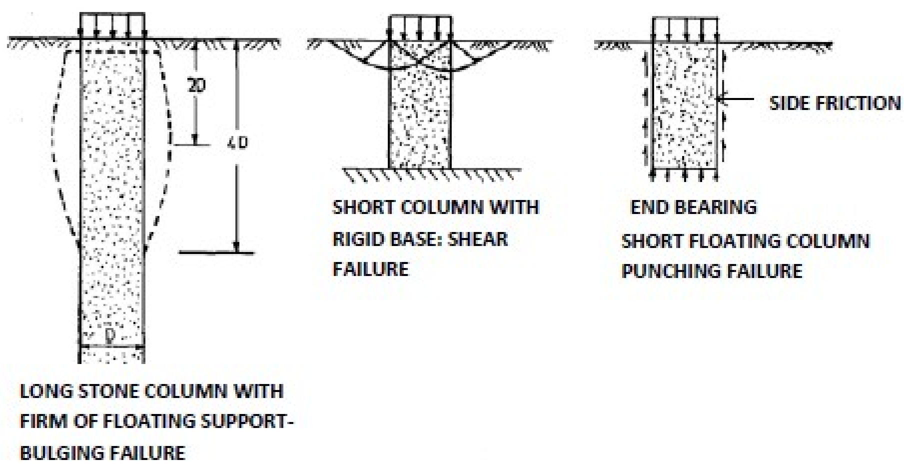



**Fig. 1.5 (a)** Failure patterns in a single stone column on a homogenous soft layer (Naik, 2013)

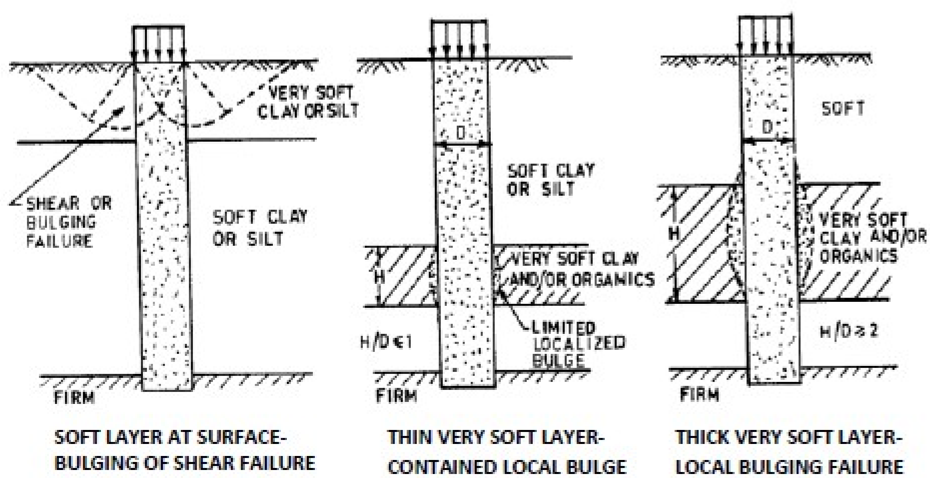



**Fig 1.5 (b)** Failure patterns in a single stone column on a non-homogenous soft layer (Naik, 2013)

## 1.7. Numerical Modeling

The validation of this project was carried out by numerical modeling using Plaxis, which is a *finite element package* particularly for the examination of deformation and stability in geotechnical projects. The finite element method is widely used for geotechnical applications and its main advantage is that it has its application in materials exhibiting non-linear stress-strain behavior. Plaxis version 9 is commercially available 2 dimensional finite element code used for analyzing deformation and stability in geotechnical problems. It can be used for plane strain as well as for axisymetric modeling.

Soil being a multi-phase material, dealing with hydrostatic and non-hydrostatic pore pressure requires special procedures. Accurate and detailed modeling of the real situation is achieved by inputting the soil layers, structure, loads as well as boundary conditions. This geometry then gives a finite element mesh which is automatically generated.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1. General

A lot of research has been done in this field. Behavior of stone columns has been observed under different conditions (different types of soil conditions), different configurations, different way of installation, use of different types of reinforcements, different types of loading and many others alterations. But the final objective being the same i.e. recording the improvement in the Bearing capacity of the ground and observing the failure pattern of the stone column.

## 2.2. Research Work on Stone Columns

**A.P. Ambily et al. [1]** studied the behavior of single column and multiple columns(group of seven column) carried out by altering different parameters like spacing between the columns, different loading rates and by changing the shear strength of the soil. Columns of diameter 100mm were made in soft clay of different consistency. The tests were carried out in 2 different ways –

- Entire equivalent area loaded to check the stiffness of ground.
- Only column area loaded to calculate the axial strength.

Pressure cells were fixed in the loading plate to calculate the actual stress on column and clay. Final results showed that multiple columns are more effective but if columns are arranged with spacing more than 3 times the diameter of the column, no significant improvement is observed.

**S. Murugasen et al. [2]** experimented on both single and multiple stone column system using the Geosynthetic encasement. Encasement prevents the bulging out of the stone column and saves the drainage function of the stone column and also increases the friction between the aggregates and the soil surface. The results from the encasement indicated that the encased stone columns are more effective then the uncased stone columns.

**R. Shivashankar et al. [3]** carried out the plate load tests on unit cells using a different reinforcing method i.e. installing vertical nails along the circumference of the stone column. Again, two types of loading was carried out- load on equivalent area & and load on the column area only. Its results showed that the effectiveness of stone columns improved by introducing vertical nails. Also, effectiveness of stone column can be more increased by-

- Increase in diameter, number & depth of the vertical nails.
- Decreasing the area replacement ratio.

**K. Ali et al. [4]** worked on both single and multiple stone columns with many other variations i.e. –

- Floating and End bearing.
- Unreinforced.
- Vertically reinforced (with geotextile and with geogrid).
- Horizontally reinforced (with geotextile and with geogrid).

Results showed that the vertical reinforcement works against bulging by generating hoop stresses, while horizontally reinforced uses friction mobilization.

**Wankyu Yoo et al. [5]** did the same tests on sand column i.e. sand compaction pile (SCP) or Gravel compaction pile (GCP). Geosynthetics encasement was used on these sand piles which are called Geotextile-Encased Sand Pile (GESP). Experiments were run on prototypes with different area replacement ratio and different tensile strengths. As a result failure reason for Geotextile-Encased Sand Pile (GESP) is buckling unlike that of sand compaction pile (SCP) i.e. bulging.

**P. Mohanty et al. [6]** studied the different the effect of different layers of soil. Two types of layering systems were formed i.e. stiff clay below soft clay & soft clay below stiff clay. Applied load on one column among all the columns of a multiple stone column system to study behaviour of one column among all the other columns. Result showed that the behaviour of the stone column is mre dependent on the upper layer of the soil.

**Mohammed Y. Fattah et al. [7]** observed the variation in the stone column behaviour by changing the distance between in between the column & by differing the length to diameter ratio of the stone column. As a result it was found that the stone columns are most effective when length to diameter ratio is in between 5 to 8 & spacing is approximately 2.5 times diameter.

**Mengfei QU et al. [8]** conducted a study on the behaviour of a stone column in case of earthquakes. And the conducted experiment showed that if acceleration remains less than 0.2g, the stone column remains unaffected. But when it reaches between 2g – 3g the Embankment's slope toe starts liquefying.

**D. Rangeard et al. [9]** conducted experiments on clayey soil reinforced with a sand column. Results were compared between the stone columns made by using different methods of installation i.e. replacement method, displacement method, with compaction and without compaction. Results turned out to be in favor of replacement method with compaction.

**Harish C et al. [10]** studied the behaviour of the stone column ( both unreinforced and reinforced ) in the black cotton soil. Studying the effect of changing the diameter of the stone column is the major aim of this paper. And also comparing the bearing capacity of the soil reinforced with stone columns encased with different length of geosynthetics.

**Shushovan Dutta et al. [11]** did a study to create a new type of encasement that can be made from waste plastic bottles and normal stone columns were not used instead fly ash columns were created. All the columns created were end bearing columns and placed in triangular and square pattern. The method turned out to be really efficient & effective.

## 2.3. Summary of Literature Review

Maximum research has been done on unreinforced stone columns. The relationship between the stones and soil is a major factor in determining the extent of ground improvement. Main cause of failure of a stone column, as observed by various experiments, is bulging. Stone columns are more efficient if they have a small cross-sectional area and are placed more compactly (for group of column). Using reinforcements helps in increasing the bearing capacity of soil.

## 2.4. Objectives

From the literature review, following objectives are determined:

1. To study the effect of *unreinforced stone column* on *bearing capacity* and *settlement characteristics* of surrounding soil.
2. To investigate the behaviour of *reinforced stone column* with *vertically* placed *geosynthetics*.
3. To investigate the behaviour of reinforced stone column with horizontally placed equidistant circular geosynthetic discs.
4. Validation of model testing with numerical modeling in finite element method using Plaxis 2D.

# CHAPTER 3
# METHODOLOGY

## 3.1. General

In this chapter, the methodology of the experimental program has been discussed. For this experiment, we designed 3 unit cells of isolated stone columns with varying reinforcement arrangements. The soil was tested for specific gravity, particle size distribution and c-Φ limits, the aggregates' particle size distribution was also studied. The prototypes were then tested under the Universal Testing Machine and their failure pattern was examined.

## 3.2. Materials Used

### 3.2.1. Soil

The soil was procured from Jaypee University of Information Technology. Tests conducted on the soil and their results are consolidated below:

1. **Direct Shear Test**

DST is a laboratory or field test used by geotechnical engineers to measure the shear strength properties of soil or rock or to measure discontinuities in soil or rock. Three or four specimens of undisturbed soil sample are tested. The specimen is put in a shear box with two stacked rings that hold the sample. Confining stress acts vertically on the specimen, and the upper ring is pulled laterally till the sample fails. Applied load and induced strain are recorded at frequent intervals to establish a stress-strain curve for each confining stress. Many specimens are tested at different confining stresses to conclude the shear strength parameters, the friction angle (Φ) and the soil cohesion (c). The results are then plotted with residual stress on y-axis and confining stress on x-axis. The slope of the curve is the friction angle and the y-intercept which fits the test results is cohesion.

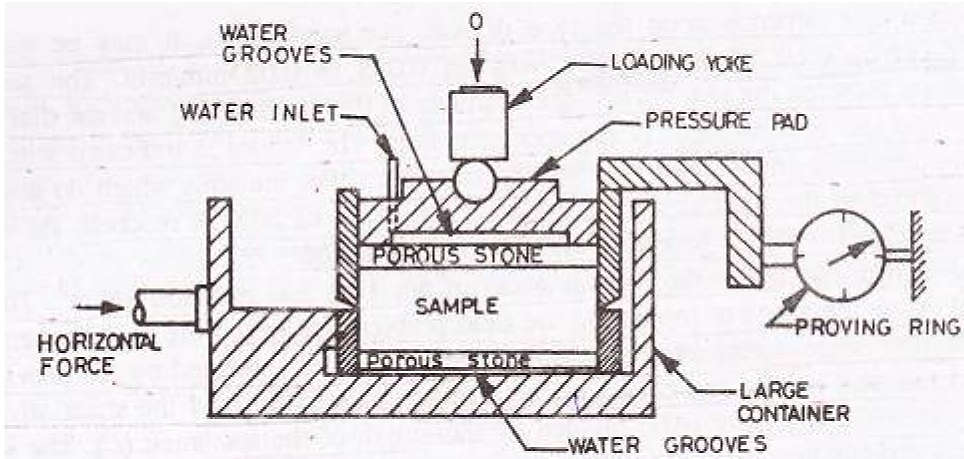



**Fig 3.1** Apparatus of Direct Shear Test

2. **Moisture Content Test**

Moisture content or water content is the quantity of water contained in a material. For soil, it is the ratio of the weight of water in the soil to the weight of solids in given soil mass. The moisture content is expressed as a percentage. The specimen is kept in an oven for 24 hours at a temperature of 110±5˚C. When the soil has dried, the specimen is taken out and weighed. This method is known as the *Oven Drying Method for Moisture Content Determination.*

The water content = $[W_2 - W_3] / [W_3 - W_1] * 100\%$ (1)

Where, $W_1$ = Weight of empty container

$W_2$ = Weight of container + wet soil

$W_3$ = Weight of container + dry soil

3. **Specific Gravity Test**

Specific Gravity is the ratio of density of a reference substance. It can also be defined as the ratio of the mass of a substance to mass of a reference substance of the same volume. The *Pycnometer method* was used, in which a bottle is filled precisely up to a specific volume, which may or may not be accurately known. The specific gravity is calculated as:

$$G = [M_2 - M_1] / [(M_2 - M_1) - (M_3 - M_4)] \quad (2)$$

Where, $M_1$ = mass of empty pycnometer

$M_2$ = mass of pycnometer with dry soil

$M_3$ = mass of pycnometer and soil and water

$M_4$ = mass of pycnometer filled with water only

**4. Proctor Compaction Test**

Optimum moisture content of soil is the moisture content at which maximum dry unit weight is obtained after given compaction effort, such that the soil has no voids. The *Proctor Compaction Test* includes compacting soil of known moisture content into a cylindrical mould having standard dimensions with the help of compaction in a controlled magnitude. The soil is filled in 3 layers with 25 blows of the rammer for compaction at each layer. After testing a number of specimens, a curve between the dry unit weight and water content is obtained. This curve then gives the optimum water content to reach the maximum dry density.

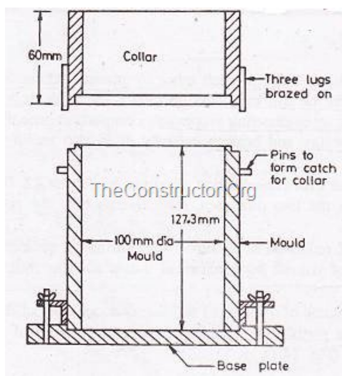



**Fig 3.2 (a)** Proctor test mould

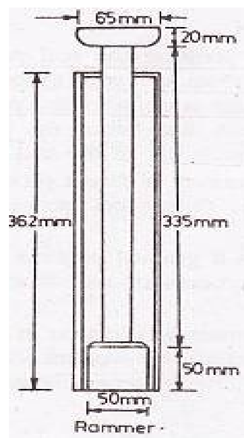



**Fig 3.2 (b)** Proctor test rammer

**Table 3.1** Consolidated results of the tests conducted on the soil sample

| Properties | |
|---|---|
| c | 0.02 kg/cm sq. |
| Ø | 20 degree |
| Water content | 3.44% |
| Specific gravity | 2.65 |
| OMC | 8.40% |
| Dry density | 1.6 g/cc |

5. **Sieve Analysis**

The gradation test or sieve analysis is used to evaluate the particle size distribution of granular material by allowing the material to pass through a group of sieves arranged in decreasing order of their mesh sizes. The sieve sizes used are 10mm, 4.75mm, 2.36mm, 1.18mm, 600microns, 300microns and 150microns. The amount of material passing through each sieve is measured and a graph is plotted correspondingly. This test helps in studying the nature of the soil. The soil used in this project was sandy in nature and its particle size distribution curve is as under:

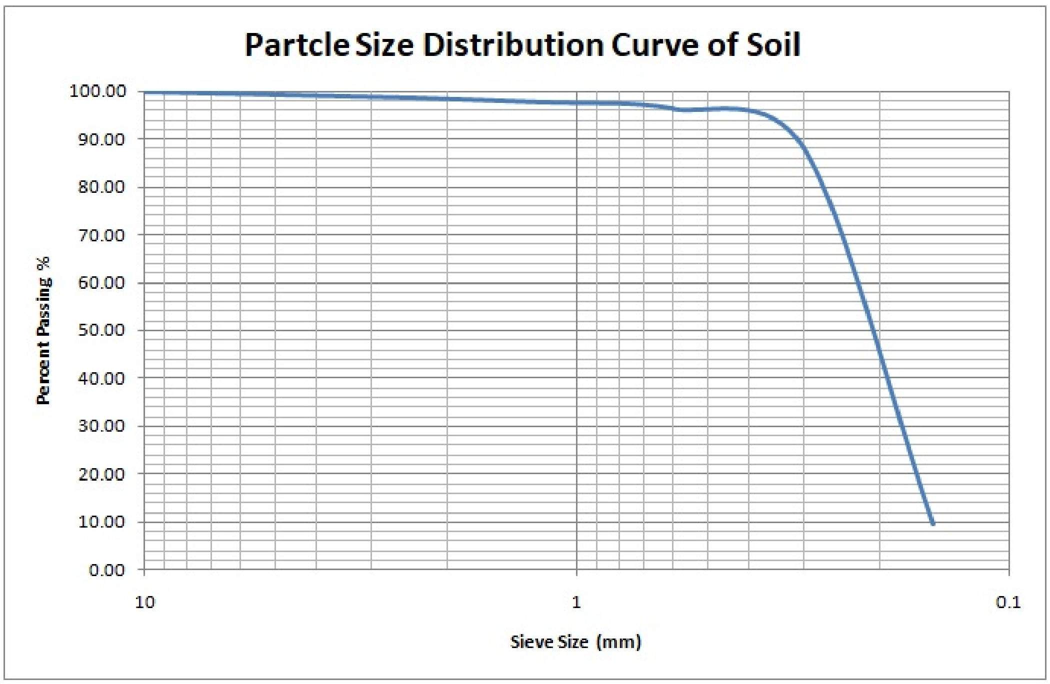



**Fig 3.3** Particle size distribution curve of soil

### 3.3.2. Aggregates

The aggregates to be used for constructing the stone column could have been between 6mm- 40mm (K.Ali et al 2014). Therefore, aggregates of *10mm (passing)* were chosen. They were procured from Hardik Construction Company, Panipat. 25% of the aggregates were retained on the 10mm sieve whereas 63% of the aggregates were retained on the 4.75mm sieve.

**Fig 3.4** Aggregates

### 3.3.3. Geotextile

Goetextiles are permeable material which can be used in association with soil to separate, filter, reinforce, protect, or drain. These fabrics come in 3 forms: woven, needle punched or heat bonded. The geotextile used for reinforcing the stone column was *Woven Polypropylene Geotextile* which had a high load capacity but wasn't very porous, thus is poor in drainage. These textiles find their application in roads, airfield, reservoirs, retaining structures, etc. They improve soil strength at a lower cost and they also allow planting on steep slopes.

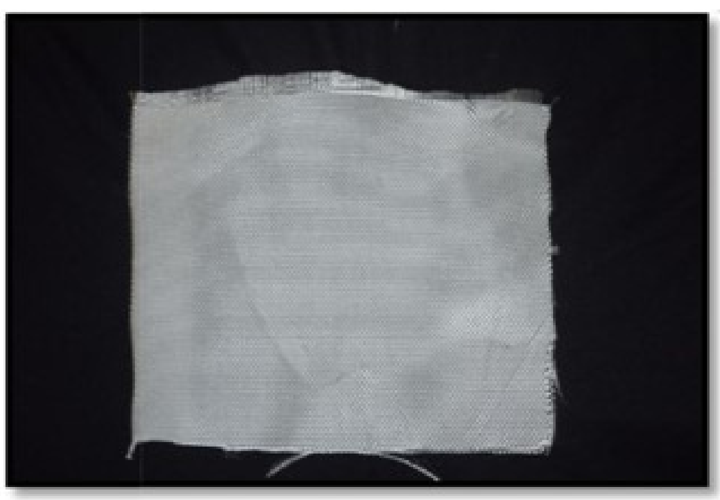


**Fig 3.5** Woven polypropylene Geotextile

**Table 3.2** Properties of Woven polypropylene Geotextile (as provided by manufacturer)

| Property | Particulars | Units | Test Method | Quality No. |
|---|---|---|---|---|
| | | | | Vt2000 |
| Tensile Strength | WARP | kN/m | IS 1969 | 45 |
| | WEFT | kN/m | IS 1969 | 34 |
| Elongation at Break | WARP | % | IS 1969 | 30 |
| | WEFT | % | IS 1969 | 28 |

### 3.3.4. Model tanks

For modeling the stone columns, 2 model tanks of dimension 300mm X 300mm X 550mm were fabricated. 3 sides of iron and 1 side of acrylic sheet were made. The figure set 3.6 depicts the model tank and its dimensions. The tank dimensions were chosen as per K.Ali et al, 2013.

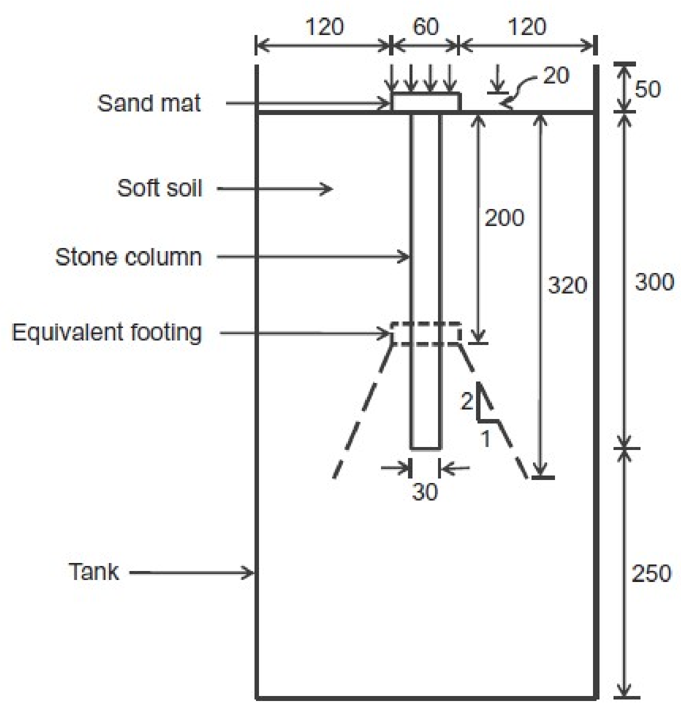



**Fig 3.6 (a)** Schematic view of isolated stone column (K.Ali et al, 2013)

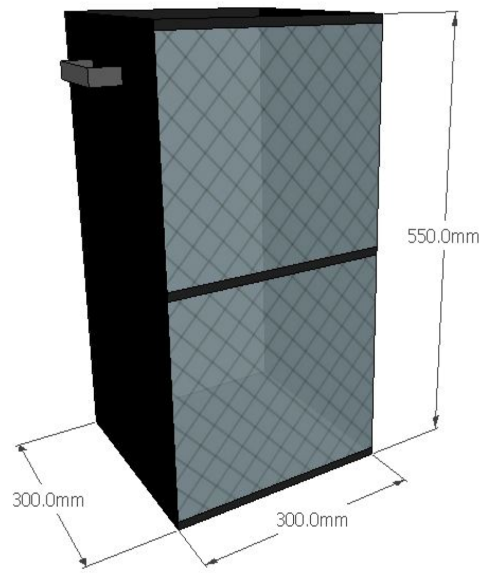


**Fig 3.6 (b)** Model tank (front view)


**Fig 3.6 (c)** Model tank (side view)

- **Unit cell**

Unit cells are defined as cylinder with an influence zone diameter hemming in the surrounding soil and one stone column. We have modeled single piles under 3 different reinforcement conditions. Unit cells allow the study of floating columns, which are the columns that are not in contact with a rigid substratum. This project studies the behavior of floating columns which are at a height of 20cm from the prototype base. For easing our study and for simplicity, this project was carried out on *isolated columns* and area greater than the stone column was loaded.

- **Hollow pipe for casting**

A hollow pipe of *diameter 40mm* was used for casting the stone columns .


**Fig 3.7** Hollow pipe of diameter 40mm

- **Iron cylinder for testing**

An iron cylinder of *diameter 80mm and height 20mm* is used for testing. The testing cylinder's diameter was chosen such that the dimension of the tank is 3-5 times the diameter of the loaded area. This is done to ensure that the tank walls do not exert any forces on the column.

**Fig 3.8** Iron cylinder used for testing

## 3.4. Experimental Program

### 3.4.1. Casting the Columns

Isolated floating columns were casted for studying the behavior of the columns and their resultant effect on the ground and its properties. To reduce the significance of the induced stresses at tank boundaries, tank boundaries were chosen such that they do not affect the stone column behavior. The ratio of column area to unit cell area, known as the *Area Replacement Ratio* is chosen to be 25% (K.Ali et al. , 2013). The isolated column approach was used and area greater than the stone column was loaded. Loading the surroundings of the column is beneficial as it increases the horizontal stresses at the lateral boundaries of columns and increases their confinement (Castro, 2017).

**a) Unreinforced Stone Column**

The column was cast in the following steps:

1. *Filling up the soil*

   The soil was filled in layers of 10cm each. After every 10cms, compaction was provided by using the rammer. Soil was compacted by giving uniform 15 blows. Thereafter, the tracer was placed and the next layer was filled up, as shown in Fig 3.9.

The soil was filled up to 50cm height from the bottom of the tank while the stone column was simultaneously cast as explained below.

**Fig 3.9** Filling up the soil in layers of 10cm each

*2. Placing the pipe and casting the column*

Since floating columns were modeled, after filling the soil up to 20cm, the hollow cylindrical pipe was placed in the model tank. The aggregates are filled in layers and light compaction is provided to the aggregates by a tamping rod. The pipe is withdrawn simultaneously while the aggregates are filled in. The aggregates are filled in till the top of the tank, i.e; up to the height till which the soil has been filled (50cm).

**Fig 3.10** Unreinforced Stone Column

**b) Vertically Reinforced Stone Column**

The vertical reinforcement was provided by using a geotextile encasement. The encasement was stitched to size of the cylindrical pipe. The following steps were followed:

*1. Filling the soil*

The soil was filled in a similar manner to the casting of unreinforced column. After compaction and tracing of 2 layers of 10cms each, the pipe was introduced.

*2. Casting the Column*

The pipe of enclosed in geotextile and then placed in the tank. To reduce friction, the external sides of the pipe were coated with grease. The aggregates were pored in and tamped lightly with a tamping rod and the pipe was withdrawn simultaneously. This procedure allowed the geotextile to act as a sort of sac to carry the aggregates.

**Fig 3.11 (a)** simultaneously withdrawing the pipe while filling in the aggregates

**Fig 3.11 (b)** Tamping the aggregates

**Fig 3.11 (c)** Vertically Reinforced Stone Column

**c) Stone Column Reinforced with Horizontal Circular Discs Placed at Equal Distances**

Circular discs of diameter equal to the diameter of the pipe were cut out from the Geotextile. The discs were to be placed at a distance of 3cm from each other. The spacing was chosen as such because the increase in strength of the column depends upon the spacing between the discs. With decrease in spacing, the increase in strength becomes higher.

*1. Marking the pipe*

The pipe is scaled at every 3cms, and the same is marked with paint to enable placing of the circular discs.

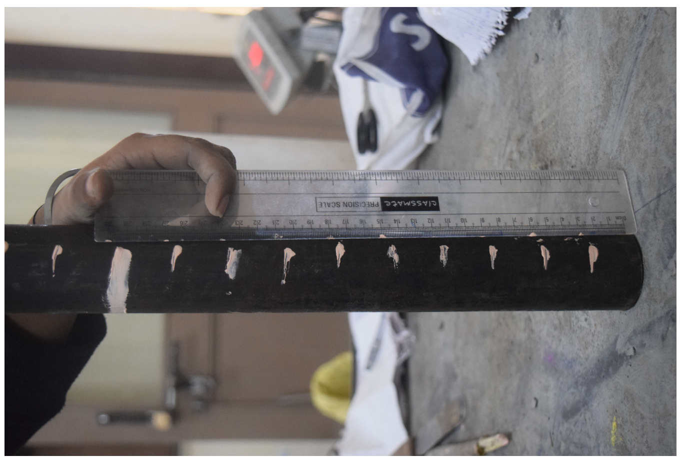


**Fig 3.12** the pipe with markings at every 3cm

*2. Circular discs*

Discs of diameter 40mm were cut out from the geotextile as shown in Fig 3.13.

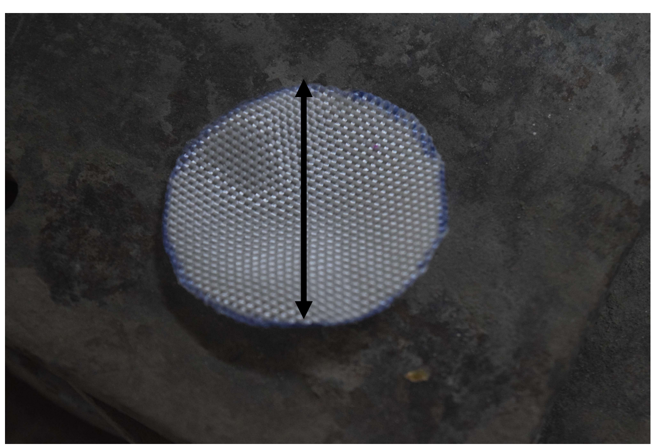


**Fig 3.13** Horizontal circular disc of diameter 40mm

*3. Casting the column*

The pipe is placed in the soil at 20cm from the bottom. The aggregates are filled in and tamped; thereafter the discs are inserted at every marking using a pipe with diameter smaller than the casting pipe. The pipe is withdrawn simultaneously.


**Fig 3.14 (a)** Casting the column while inserting the discs and simultaneously pulling out the pipe


**Fig 3.14 (b)** Placing the circular Geotextile disc


**Fig 3.14 (c)** Horizontally Reinforced Stone Column

### 3.4.2. Testing the Prototypes

The testing was done using the *Universal Testing Machine (UTM)*. The UTM is a machine used for testing the tensile and compressive strength of materials. It consists of a load frame, a load cell, a cross head, an output device and certain test fixtures. When the specimen is placed between the cross heads, and the machine is switched on, a uniformly increasing load is applied on the specimen by the UTM. The load and the resultant settlement are displayed on the output device.

The load was applied at the *rate of 1kN/min* till a *settlement of 60mm* was reached as shown in Fig 3.15(a) - (f). Thereafter, the columns were compared for analysis of the increment in strength.

**Fig 3.15 (a)**

Unreinforced stone column before settlement

**Fig 3.15 (b)**

unreinforced stone column after settlement

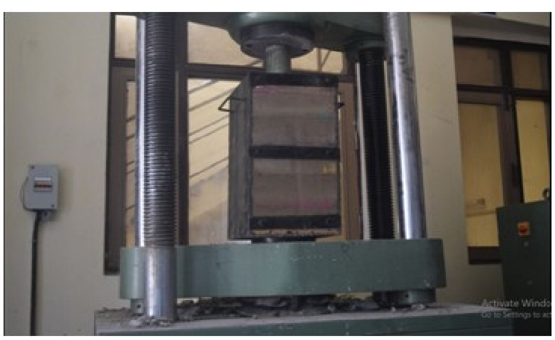


**Fig 3.15 (c)**

Vertically Reinforced column before setllement

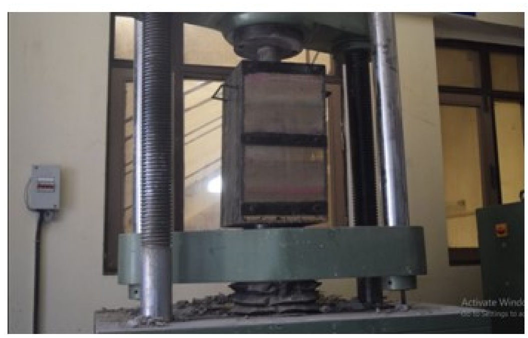


**Fig 3.15 (d)**

Vertically reinforced column after settlement

**Fig 3.15 (e)**

Horizontally reinforced column before settlement

**Fig 3.15 (f)**

Horizontally reinforced column after settlement

The settlement was photographed and compared. The columns settled in by 60mm, as shown in Fig 3.16(a) - (f).

**Fig 3.16 (a)** Unreinforced column before settlement

**Fig 3.16 (b)** Unreinforced column after settlement

**Fig 3.16(c)** Vertically reinforced column before settlement

**Fig 3.16(d)** After settlement

**Fig 3.16(e)** Horizontally reinforced column before settlement **Fig 3.16(f)** After settlement

The columns experienced failures at different loads due to the varying reinforcement arrangements and their resulting effect on the increase in the bearing capacity of the soil. As we modeled floating columns, penetration into the soil was experienced early on, before the development of significant hoop stresses (K.Ali et al, 2013)

### 3.4.3 Excavation of the Columns

To study the failure pattern of the columns, excavation of the columns was done. The expected failure pattern was that the columns would experience failure due to bulging at the neck (K.Ali et al, 2013). The procedure used for excavation and the failure pattern thus obtained has been described as under:

#### a) Excavating the Unreinforced Stone Column

Since complete excavation would lead to possible disintegration of the unreinforced column, partial excavation was carried out.

**Fig 3.17** Excavated unreinforced stone column

The perpendicular distance between the neck of the column and the perpendicular distance between the bottom of the column to the wall was measured to study the failure pattern.

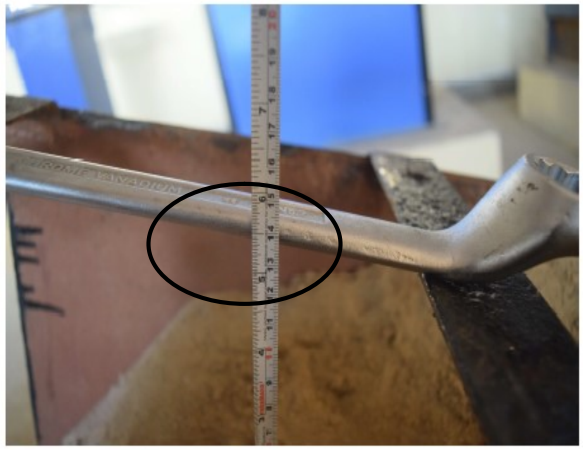


**Fig 3.18 (a)** Perpendicular distance between the neck of the column and the wall of the model tank

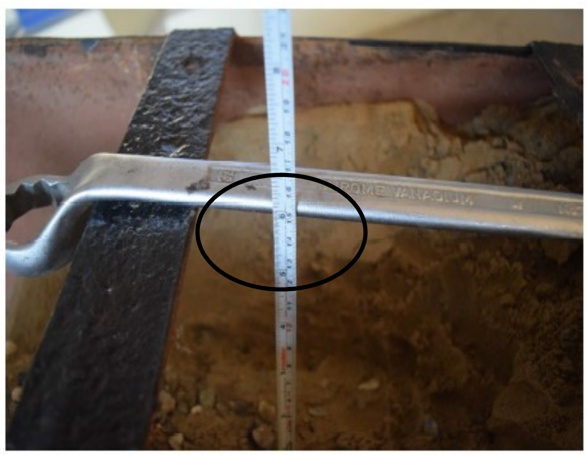


**Fig 3.18 (b)** Perpendicular distance between the bottom of the column and the wall of the model tank

As is observed from figure set 3.18, the perpendicular distance between the neck of the column and the wall of the tank is 14cm, whereas the distance between the bottom of the column and the wall of the tank is found to be 15cm. This implies that since the former distance is less than the latter, *the column experienced failure due to bulging at the neck.*

**b) Excavating the Vertically Reinforced Stone Column**

Since the reinforcement acted as a sac and thus prevented the disintegration of the column, excavation was carried out of the column, starting from the top and progressing further down into the model tank. The failure pattern so observed was then photographed.

**Fig 3.19 (a)** Excavated stone column with bulging at the neck (side view)

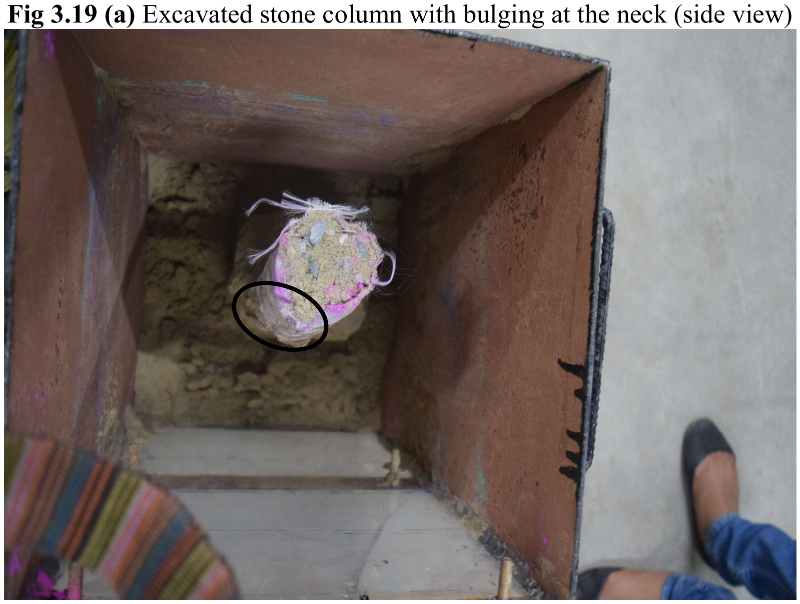


**Fig 3.19 (b)** Excavated stone column (top view)

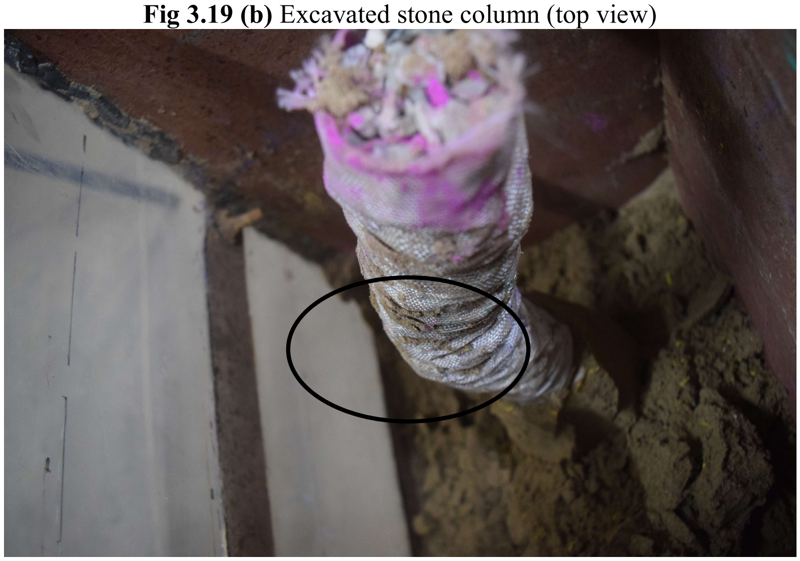


**Fig 3.19 (c)** Excavated stone column with bulging at the neck (side view)

As is observed from the above figure set, the vertically reinforced stone column also experienced failure due to bulging at neck.

### c) Excavating the Horizontally Reinforced Stone Column

The horizontally reinforced column was also excavated in a manner similar to the vertically reinforced column. After a while, the column disintegrated and the failure pattern was studied by the imprint that it left behind on the surrounding soil. The same has been depicted below by the Fig set 3.20 (a) – (e).

**Fig 3.20 (a)** Top view of the column during excavation

**Fig 3.20 (b)** Top view of the column after excavation depicting bulging at neck

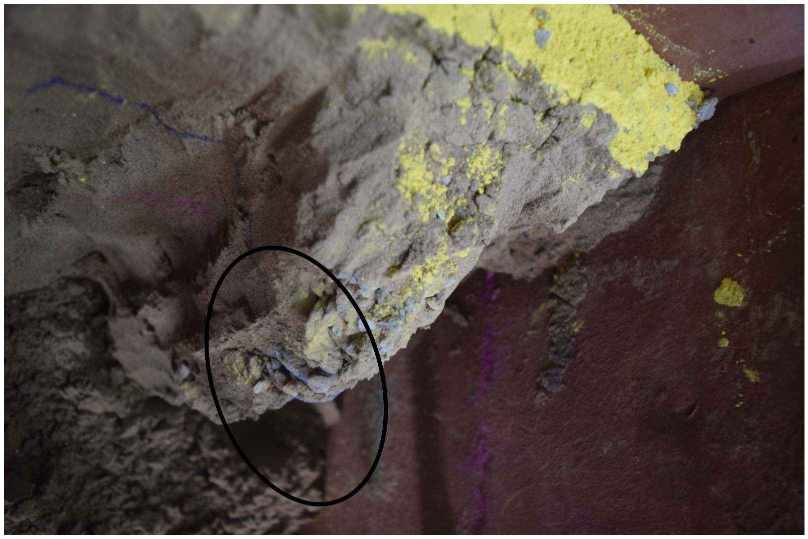


**Fig 3.20 (c)** Side view of the column after excavation depicting bulging at neck

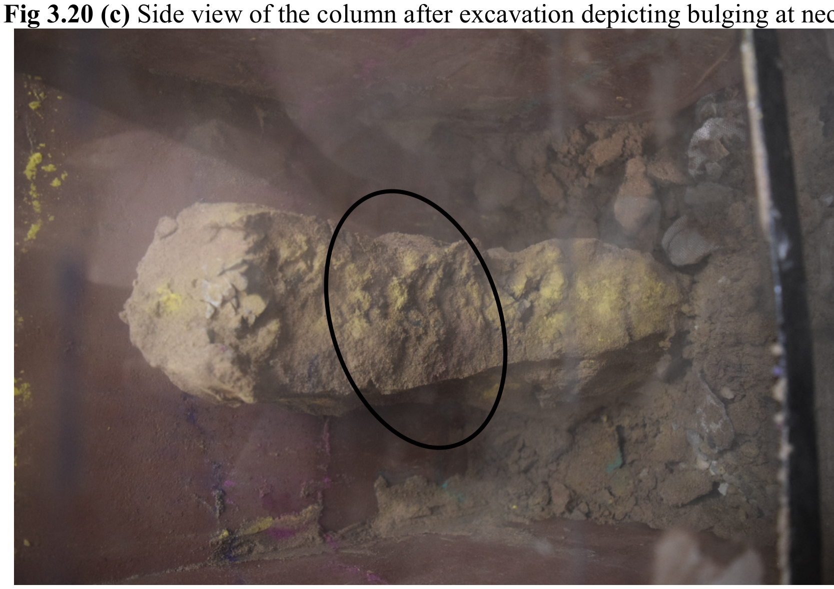


**Fig 3.20 (d)** Front view of the soil after the column has disintegrated

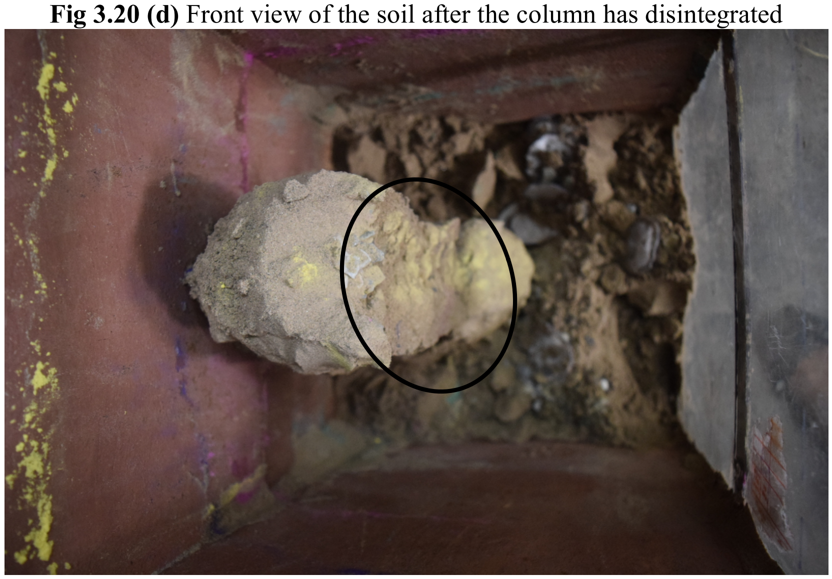


**Fig 3.20 (e)** Top view of the soil after the column has disintegrated

Thus, all 3 columns experienced failure due to bulging at the neck as observed by K.Ali et al, 2013. This failure patter n is also in accordance with Wood et al, who observed that with increase in the area replacement ratio, columns bulge more in the upper zone of the soil layers while subsequently transferring load to a greater depth. Floating stone columns may fail in end bearing in the weak underlying layer before a bulging failure can develop, however, for the sub surface conditions that are generally met in practice, bulging is the common controlling failure mechanism (Harish et al., 2016).

# CHAPTER 4
# NUMERICAL ANALYSIS

## 4.1 GENERAL

There are two branches of analysis that are employed in the industry; 2-D modeling and 3-D modeling respectively. While 2-D modeling is a simple process and does not need a high end processer, it tends to yield less accurate results as compared to 3-D modeling which delivers much more accurate results but requires a high-end processor for the computation. The software used for the analysis and validation of this project is Plaxis-2D.Plaxis-2D is a finite element package used for 2-D analysis of deformation and stability in geotechnical engineering and rock mechanics. Plaxis 2D has been developed as an advanced and extended package, to include advanced soil models, static elastoplastic deformation, stability analysis, consolidation, updated mesh analysis and steady-state groundwater flow.For the purpose of validating this project, using finite analysis, a finite element mesh was created, material properties of soil and geotextile were specified. Thereafter, the boundary conditions need to be specified. To develop a finite element model, a 2-D geometry model was created, positioned in the XY-plane. Based on the input provided, suitable finite element mesh, material properties and boundary conditions are robotically performed by Plaxis at an elementary level. The final part of a series of inputs engaged, the generation of pore water pressure and initial effective stresses. For our consideration, there was no generation of pore water pressure.

## 4.2 Material Properties

As a first request estimate of the genuine soil conduct, Mohr-Coulomb display has been chosen as the material model. For our project, the model requires 5 input parameters, in particular, Young's modulus E, Poisson's proportion ν, cohesion c, friction angle of soil φ, and a dialatancy angle ψ. While replicating the drained behavior, no excess pore water pressures were produced, which is fundamentally our case.

The saturated and unsaturated unit weights and strength parameters of the soil were determined in the lab. The values obtained from the testing were used for input in the numerical modeling. In case of Poisson's ratio and dialatancy angle, standard values for sand have been used. The soil parameters are as shown in Table 4.1.

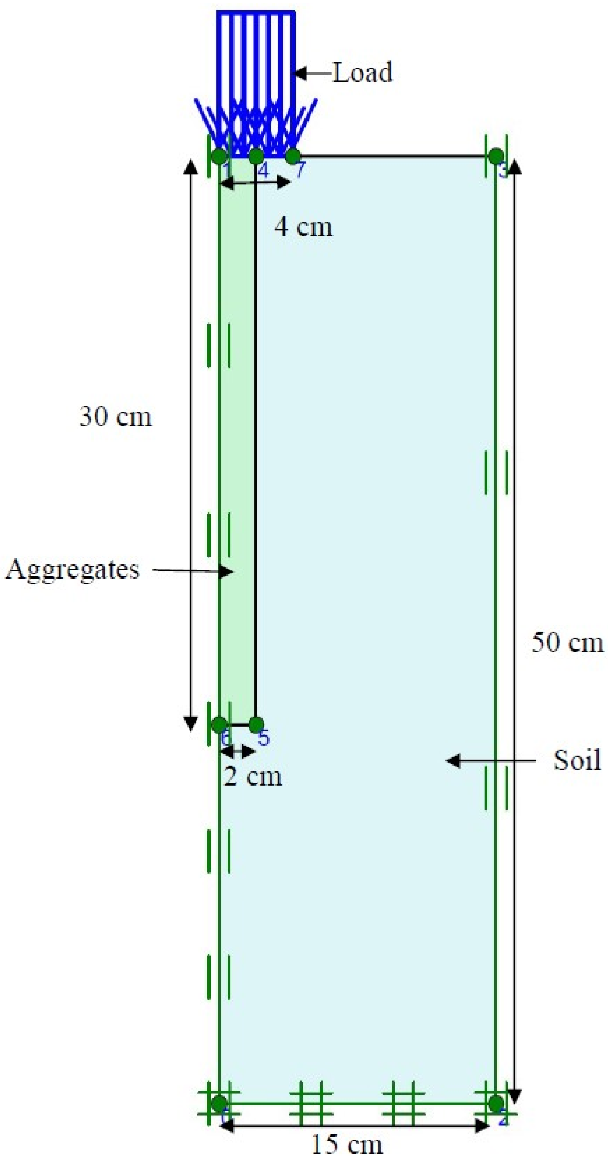
**Table 4.1** Material Properties Used in Numerical Modeling

| **Soil Properties** | |
|---|---|
| Poisson's Ratio | 0.3 |
| Friction angle, degrees | 20 |
| Dilation angle, degrees | 4 |
| Cohesion, $kN/m^2$ | 1.96 |
| Young's Modulus, $kN/m^2$ | 20,000 |
| $\gamma_{unsat,}$ $kN/m^3$ | 19.65 |
| $\gamma_{sat,}$ $kN/m^3$ | 21.76 |
| **Aggregate Properties** | |
| Poisson's Ratio | 0.3 |
| Friction angle, degrees | 43 |
| Dilation angle, degrees | 10 |
| Cohesion, $kN/m^2$ | 0.1 |
| Young's Modulus, $kN/m^2$ | 55,000 |
| $\gamma_{unsat,}$ $kN/m^3$ | 22.78 |
| $\gamma_{sat,}$ $kN/m^3$ | 23.24 |
| **Reinforcement (Geotextile) Properties** | |
| Mass per unit area, $g/m^2$ | 200 |
| Stiffness, kN/m | 150 |
| Modulus of Elasticity (E), $kN/m^2$ | 150,000 |
| Tensile Yield Strength ($N_p$), kN/m | 45 |
| EA, kN/m | 75,000 |

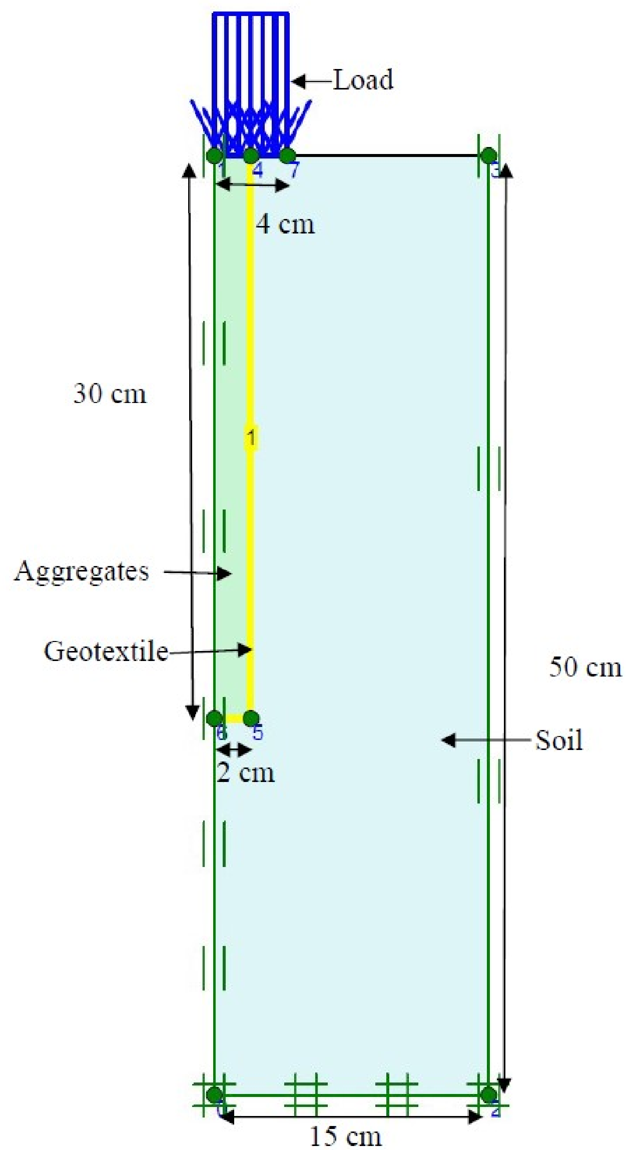
Geotextile reinforcement was modeled using the “geogrid” element. The geogrid element possesses only one (axial) degree of freedom at each node, and is subjected to tensile forces only. Geotextile properties used for modeling have been tabulated in Table 4.1.

## 4.3 Model Configuration

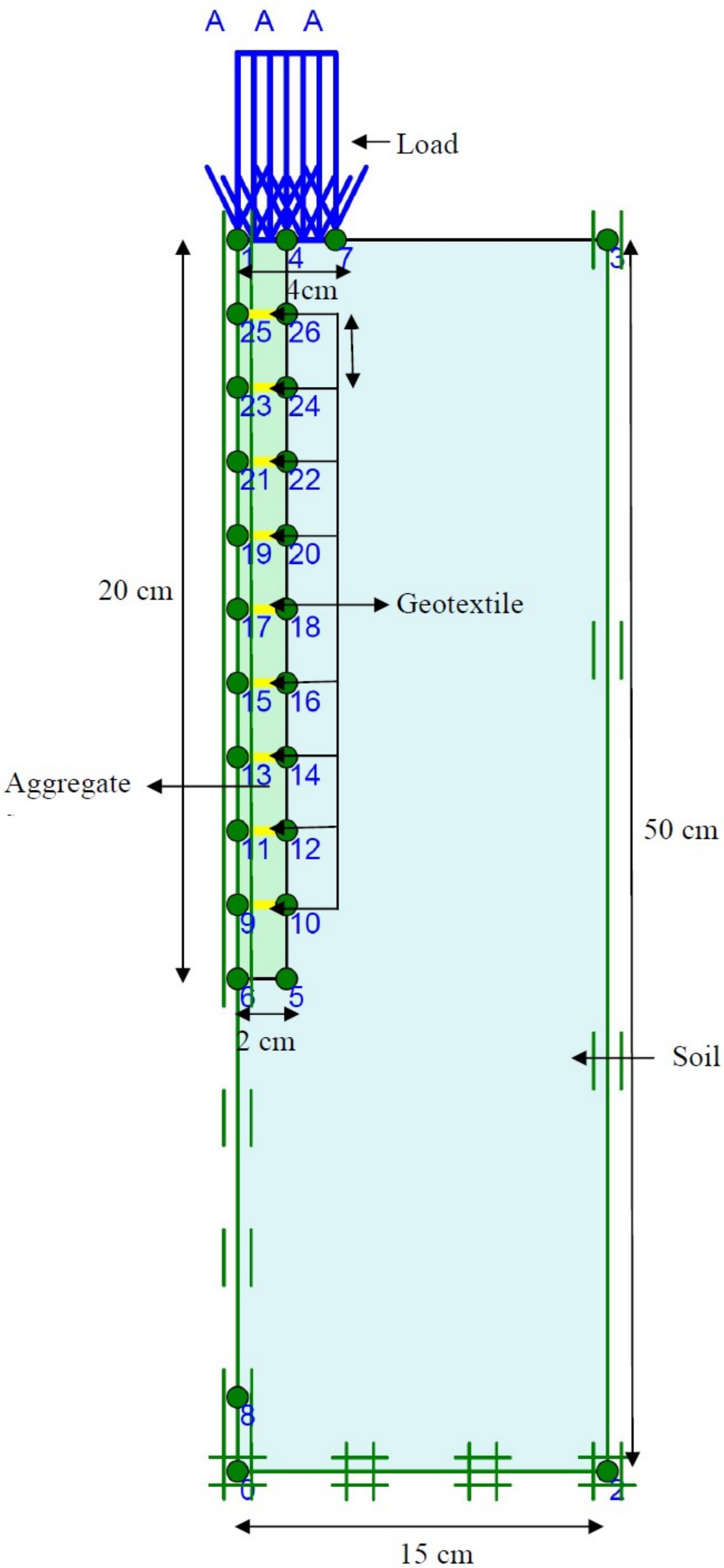
The configured model used for analysis is as depicted in Figure set 4.1. The model is indicative of the geometry and boundary conditions as simulated in the analysis.




Unreinforced column
**(a)**




Vertically reinforced column
**(b)**




Horizontally reinforced

**(c)**

**Fig. 4.1** Geometry Model with all structural elements

## 4.4 Mesh Generation

Once the geometry of the model is characterized and material properties are assigned, there arises a need to divide the geometry into finite elements in order to permit finite element calculations. This organization of finite elements is called a mesh. Plaxis 8.0 permits fully automatic mesh generation in majorly these forms – very coarse, coarse, medium, fine and very fine. The vertical and horizontal boundaries were considered to be fixed in their respective directions. The stability of the foundation soil does not form a part of this analysis and thus the bottom boundary of the model has been simulated as a fixed boundary. Figure set 4.2 depicts the generated mesh.

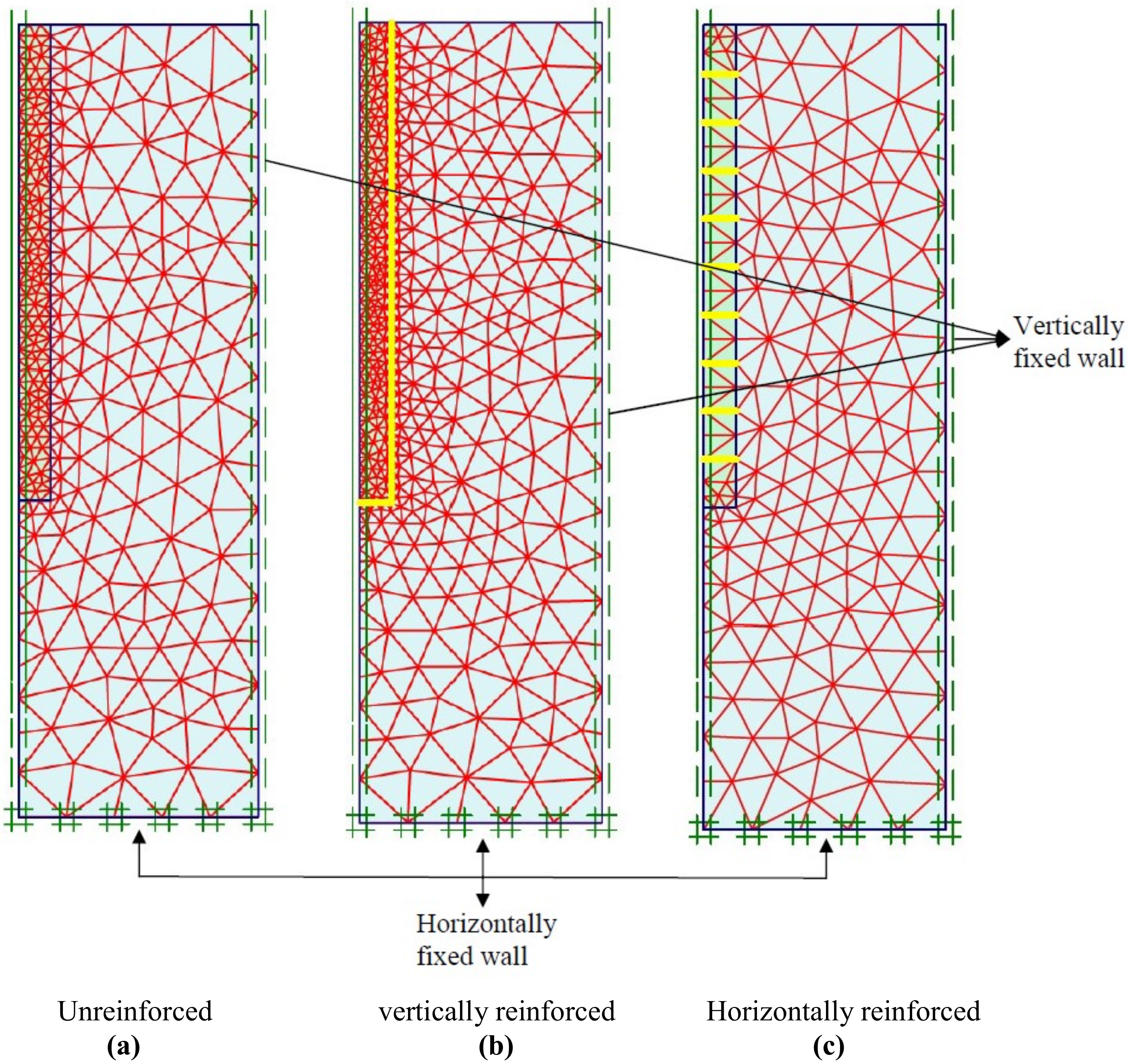
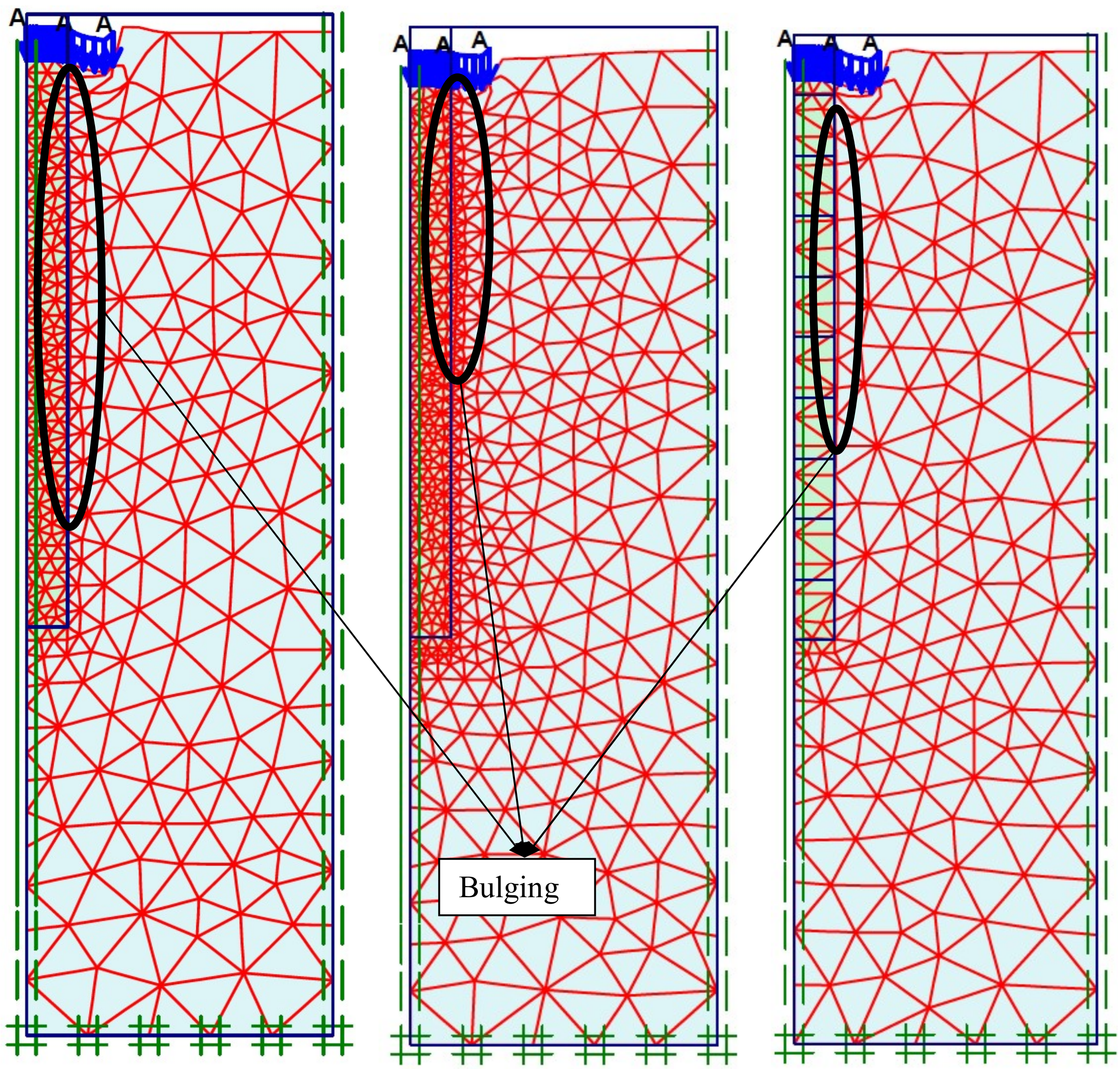



**Fig. 4.2** Initial Mesh Generated

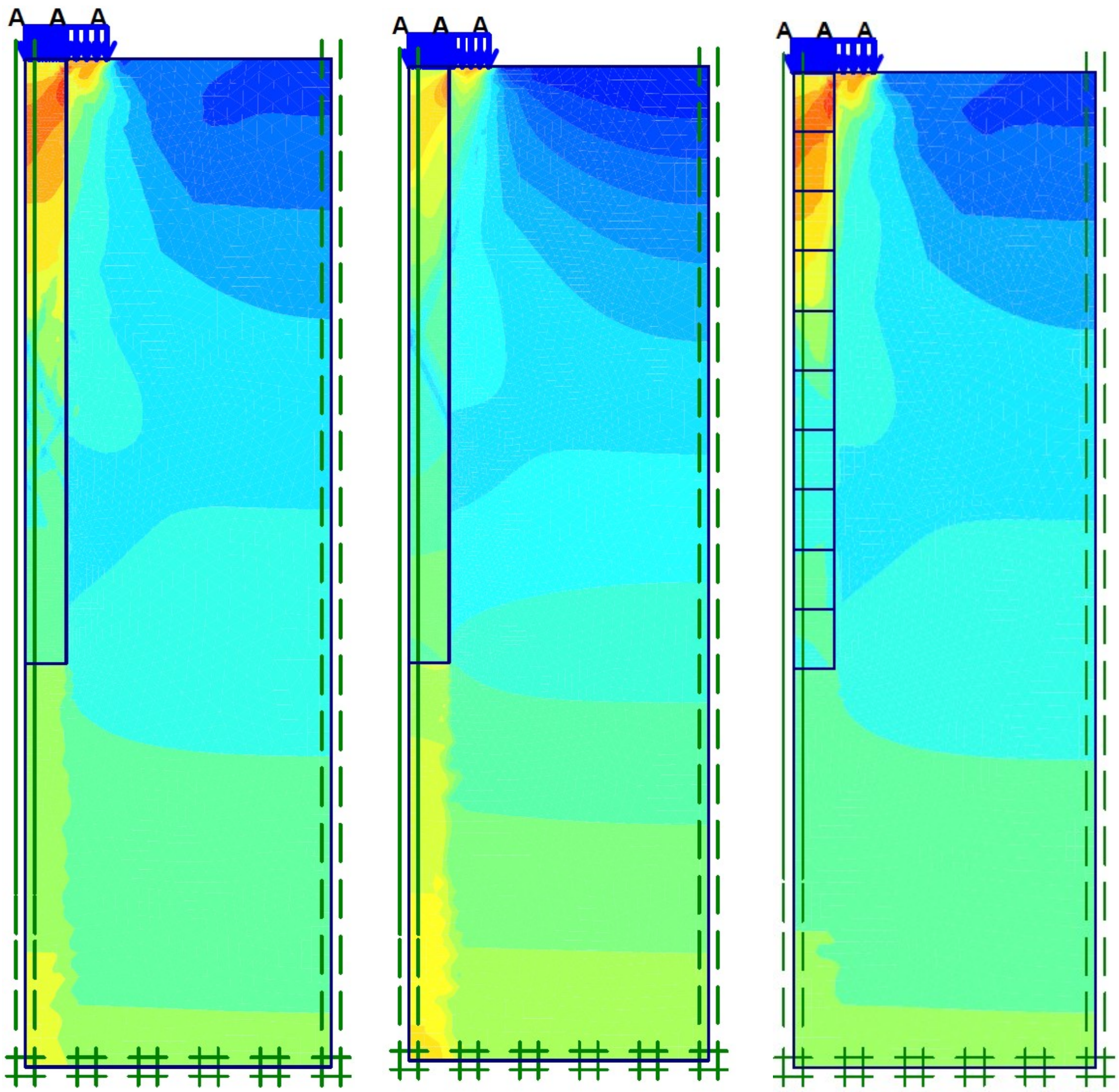



Unreinforced (b) vertically reinforced (b) Horizontally reinforced (c)

**Fig. 4.3** Mesh Generated after load application

## 4.5 Stress Distribution and Loading

A uniformly distributed load was applied to the simulated model. The loading is presented is Figure set 4.4. The final loads achieved in the testing of the stone columns at 60mm settlement, i.e. 9.8kN for unreinforced, 11.9kN for vertically reinforced & 15.8kN for horizontally reinforced column were applied.




Unreinforced (c) vertically reinforced (b) Horizontally reinforced (c)

**Fig. 4.4** Stresses Generated after load application

Comparing the stresses generated in all the 3 cases, it can be observed that the red portion is most prominent in the case of unreinforced column while it is least prominent in the case of vertically reinforced column. This implies that the stresses generated in the unreinforced column are greater in magnitude than the stresses generated in the reinforced columns.

# CHAPTER 5
# RESULT AND DISCUSSION

## 5.1 General

In this chapter, the results from model testing and numerical modeling have been depicted. The load- settlement behavior obtained for the unreinforced, vertically reinforced and the horizontally reinforced stone columns has been analyzed to study the relative improvement in the bearing capacity of soil. Stiffness improvement factor of the columns has been calculated to examine the suitability of the reinforcement patterns. Results so obtained have been validated using Plaxis 2D.

## 5.2 Results from Model Testing

### 5.2.1 Increase in Bearing Capacity

As observed in chapter 3, all three columns experienced failure at the neck due to bulging. In case of floating columns, applied vertical stresses become high enough to cause penetration and thus failure of the columns before net outward force becomes significant and causes bending (K.Ali et al, 2013). Unreinforced columns fail at a lower load than reinforced stone columns, thus increasing the bearing capacity by a lesser increment. This happens because the geotextiles transfers load to the sides as well as the bottom of the tank by developing hoop stresses and mobilizing friction.

The load-settlement behavior and the variation in axial stress with settlement for the different columns are as given in Fig set 5.1.

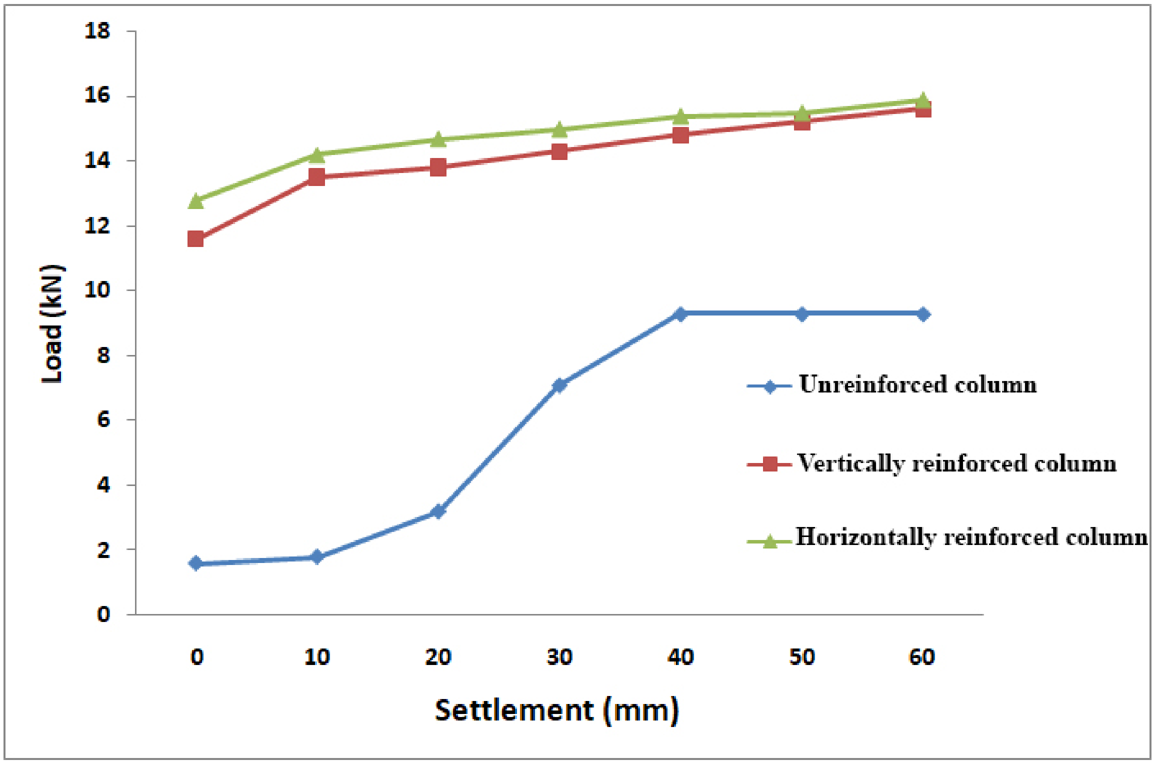



**Fig 5.1(a)** Load settlement behavior for the model testing results

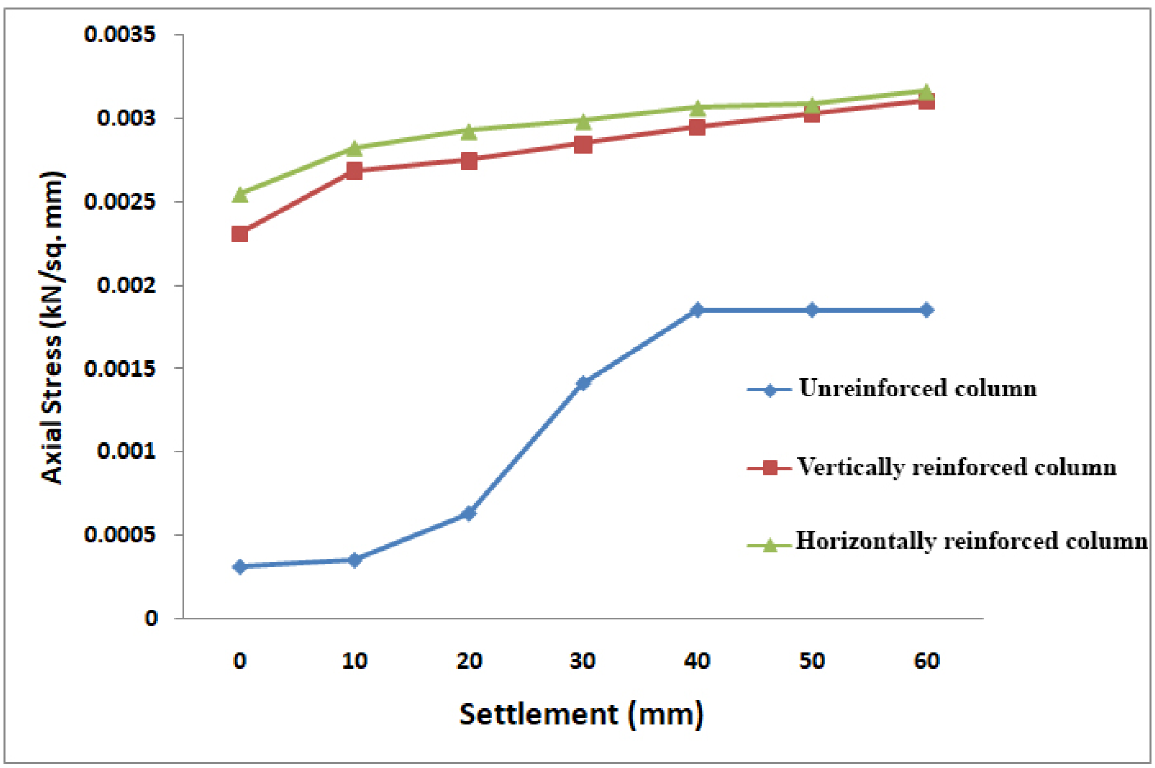



**Fig 5.1(b)** Variation in axial stress with settlement

From the graphs, the following inferences have been made:

- Unreinforced column starts experiencing settlement very early, at a loading of less than 2kN and an axial stress being less than 0.5kN/mm sq.
- Up to 40 mm settlement, the unreinforced column bears a load of around 9.8kN and an axial stress of around 1.9kN/mm sq. Thereafter, the column keeps on settling without bearing any load. The load and axial stress graphs become constant, which implies that *the unreinforced column fails at 9.8kN.*
- Vertically reinforced column does not start settling up to a load of 11.9kN and an axial stress of 2.3kN/mm sq, thereafter, it starts settling.
- Unlike the unreinforced column, the vertically reinforced column does not fail up to a load of 15.8kN and an axial stress of 3.1kN/mm sq at which 60mm settlement is achieved. This implies that the *bearing capacity of soil increases more for vertically reinforced column than for the unreinforced column.*
- Horizontally reinforced column with equidistant circular discs does not experience any settlement up to a loading of 12.5kN and an axial stress of 2.5kN/mm sq.
- Similar to the vertically reinforced column, the horizontally reinforced column also does not fail till a settlement of 60mm is reached at which the load applied is 15.9kN and the axial stress developed is 3.2kN/mm sq. This implies that the *bearing capacity of soil increases most for the column which has been reinforced horizontally using circular discs.*
- As per the studies done on soils like clay, (K.Ali et al, 2013 and Murugesan et al, 2007) the vertical reinforcement should have performed better than the horizontal reinforcement. But since our soil was sandy in nature, *horizontal reinforcement proved to be more effective than vertical reinforcement.*

**5.1.2 Stiffness Improvement Factor (β)**

The stiffness improvement factor can be found by the following formula:

$\beta = (E_{improved} - E_{unimproved}) / E_{unimproved}]$ X 100 (1)

Where,

$E_{unimproved}$ = modulus of elasticity of the vertically or horizontally reinforced column

$E_{unimproved}$ = modulus of elasticity of the unreinforced column

E is the modulus of elasticity and is equal to the slope of the linear portion of the stress-strain curve obtained from the load settlement curve of each of the columns.

$E_{unimproved} = 27.28$ N/ mm$^2$

$E_{improved} = 51.21$ N/ mm sq (Vertically Reinforced Column)

$E_{improved} = 55.54$ N/ mm sq (Horizontally Reinforced Column)

1. **Stiffness Improvement Factor for Vertically Reinforced Column**

$\beta = 87.72$ (2)

2. **Stiffness Improvement Factor for Horizontally Reinforced Column**

$\beta = 103.60$ (3)

As is observed from equations (2) and (3),

$\beta_{vertical} = 87.72$ and $\beta_{horizontal} = 103.60$, thus we can infer that *horizontal reinforcement is better suited for improving the soil properties than vertical reinforcement.*

## 5.2 Numerical Modeling Results

Numerical modeling has given results similar to the results obtained from model testing. The columns were loaded according to the final load obtained from model testing at a settlement of 60mm.

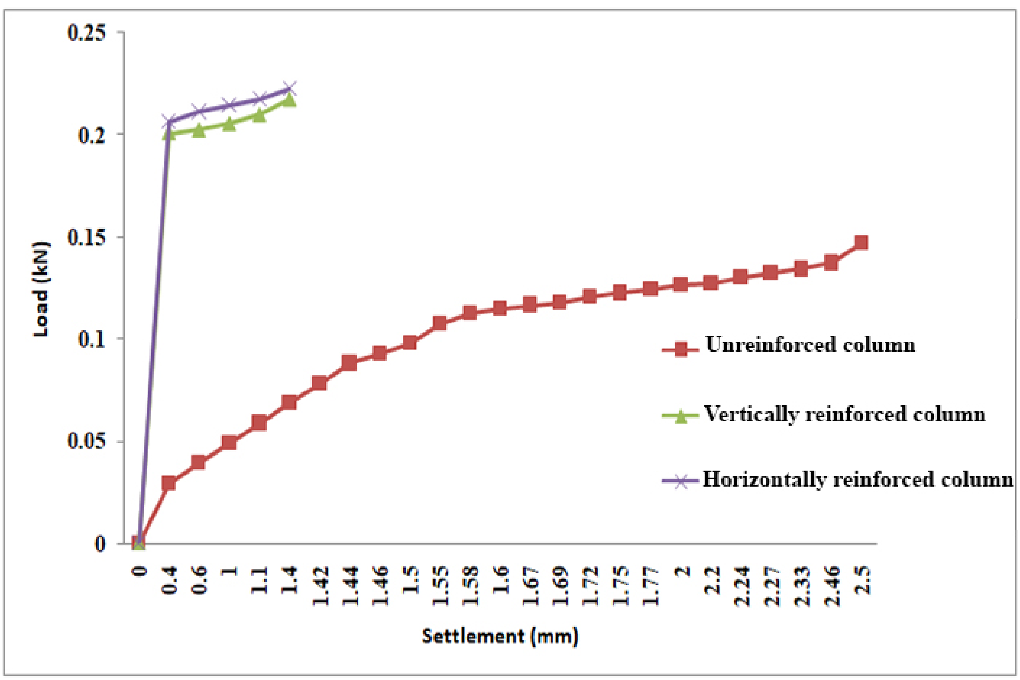



**Fig 5.2** Load –settlement behavior as obtained from Plaxis 2D

- *Unreinforced stone column* settle by 2.5mm at a factored loading of 1.6kN.
- *Vertically reinforced stone column* settled by 1.4mm at a factored loading of 2.23kN.
- *Horizontally reinforced stone column* settled by 1.3mm at a factored loading of 2.23kN.

## 5.3 Discussion

**Table 5.1** Final results obtained from model testing and numerical modeling

| **Type of Stone Column** | **Final Load Applied (kN)** | **Final Axial Stress (kN/ mm$^2$)** | **Settlement as obtained by numerical modeling (mm)** |
|---|---|---|---|
| Unreinforced | 9.8 | 0.002 | 2.5 |
| Vertically reinforced | 15.8 | 0.003 | 1.4 |
| Horizontally reinforced | 15.9 | 0.003 | 1.3 |

- The columns settled by 60mm in model testing but by 2.5mm, 1.4mm and 1.3mm for unreinforced, vertically reinforced and horizontally reinforced respectively under the same magnitude of loading because:
    1. The installation method used for construction of stone columns and its effects have not been modeled in the numerical analysis.
    2. The tank boundaries exert pressure on the column in model testing, thus forcing the soil to bulge out horizontally and cause a larger settlement. In numerical modeling however, the tank boundaries do not effect the settlement as we have only specified that vertical displacement of the columns is taking place.

    Therefore, the difference between numerical modeling and model testing has been observed.

# CHAPTER 6
# CONCLUSIONS

## 6.1 General

In this chapter, conclusions about the project, based on the results obtained from model testing and numerical modeling have been made. The increments observed in bearing capacity of the soil resulting from stone column installation have been consolidated. Numerical modeling gave similar results.

## 6.2 Conclusions

From the model testing and numerical modeling carried out on the unreinforced, vertically reinforced and horizontally reinforced isolated stone columns, the following conclusions have been made:

- Vertically encased stone column provided a 61.2% increment in bearing capacity whereas horizontal reinforcement provides an increment of 62.2% in the bearing capacity, as can be observed from the model testing results.
- The stiffness improvement factor for vertically reinforced column was found to be **87.72** while for horizontally reinforced column, it was found to be **103.6.**
- Vertically encased stone column settles 44% less, as compared to unreinforced stone column while horizontally reinforced decreases the settlement by 48%, in comparison to the unreinforced stone column as can be observed from the numerical modeling results.
- The stresses developed in numerical modeling were found to be maximum for vertically reinforced stone column.
- Horizontal reinforcement is most effective for stone columns and for their use as a ground improvement technique in sandy soils.

## 6.3 Scope for Future Work

The purpose of this project was to investigate the behavior and performance of stone columns with different configurations of reinforcement. In future, the reinforcement used can be changed. Instead of geotextiles, geoenets or geogrids may be used. This project examined the behavior of isolated floating for future study, group columns and/or end-bearing columns may be studied. Use of cohesive soils like clays and studying the effect of stone columns on them is also possible.

# References

1. A.P. Ambily and Shailesh R. Gandhi. (2007). "Behavior of Stone Columns Based on Experimental and FEM Analysis." J. Geotech. Geoenviron. Eng. 2007.133:405-415.

2. S. Murugesan and K. Rajagopal. (2010). "Studies on the Behavior of Single and Group of Geosynthetic Encased Stone Columns." J. Geotech. Geoenviron. Eng. 2010.136:129-139.

3. R. Shivashankar, M. R. Dheerendra Babu, Sitaram Nayak and R. Manjunath. (2010). "Stone Columns with Vertical Circumferential Nails: Laboratory Model Study." Geotech Geol Eng (2010) 28:695–706.

4. Mohamed Basheer, Dardeer Elsawy, Aswan, Egypt(2010). "Highway Embankment Constructed on Soft Soil Improved by Stone Columns with Geosynthetic Materials." Institute of Geotechnical Engineering, Department of Civil Engineering, Faculty of Engineering, Duisburg-Essen University Essen, 2010.

5. Jorge Castro, César Sagaseta (2013). "Influence of elastic strains during plastic deformation of encased stone columns." Geotextiles and Geomembranes 37 (2013) 45-53.

6. Jajati Keshari Naik (2013). "Load carrying capacity of stone columns embedded in compacted pond ash." Department of civil engineering national institute of technology rourkela-769008, 2013.

7. K.Ali, J.T. Shahu and K.G. Sharma. (2014). “Model tests on single and groups of stone columns with different geosynthetic reinforcement arrangement.” Geosynthetics International ·January 2014.

8. Wankyu Yoo, Byoung-Il Kim and Wanjei Cho. (2014). “Model Test Study on the Behavior of Geotextile-Encased Sand Pile in Soft Clay Ground.” KSCE Journal of Civil Engineering (2015) 19(3):592-601.

9. P. Mohanty and M. Samanta. (2015). “Experimental and Numerical Studies on Response of the Stone Column in Layered Soil.” Int. J. of Geosynth. and Ground Eng. (2015) 1:27.

10. Mohammed Y. Fattah, A.M.ASCE, Bushra S. Zabar and Hanan A. Hassan. (2016). “Experimental Analysis of Embankment on Ordinary and Encased Stone Columns.” International Journal of Geomechanics, © ASCE, ISSN 1532-3641.

11. Mengfei QU, Qiang XIE, Xinwen CAO, Wen ZHAO, Jianjun HE, Jiang JIN. (2016). “Model test of stone columns as liquefaction countermeasure in sandy soils.” Higher Education Press and Springer-Verlag Berlin Heidelberg 2016.

12. Rangeard, D., Phan, P. T. P., Martinez, J., and Lambert, S. “Mechanical Behavior of Fine-Grained Soil. Reinforced by Sand Columns: An Experimental Laboratory Study,” Geotechnical Testing Journal, Vol. 39, No. 4, 2016, pp. 648–657, doi:10.1520/GTJ20150152. ISSN 0149-6115.

13. Harish C, M S Nagaraja Gupta, Radhika K N and ManjunathItagi. (2016) “Effect of Sand column with and without encasement of Geosynthetics in Black cotton soil.” International Research Journal of Engineering and Technology (IRJET), Volume: 03, July-2016.

14. Sushovan Dutta, S.M.ASCE and J. N. Mandal. (2017). "Model Studies on Encased Fly Ash Column–Geocell Composite Systems in Soft Clay" American Society of Civil Engineers – 2017.

15. Sareesh Chandrawanshi and Rakesh Kumar (2017). "Effect on settlement reduction due to method of construction of stone column: An experimental small scale study." International Journal of Civil Engineering and Technology (IJCIET) Volume 8, Issue 6, June 2017, pp. 99–108, Article ID: IJCIET_08_06_012.

16. The constructor, < https://theconstructor.org/geotechnical/shear-strength-of-soil-by-direct-shear-test/3112/ >

17. Research Gate, < https://www.researchgate.net/figure/Standard-proctor-compaction-apparatus-Theory-Compaction-is-a-process-by-which-the-soil_fig2_309477120 >