Performance Evaluation of Stone Column Installed Soft Ground- A Parametric Study with Numerical Investigation

D.V. SivaSankara Reddy, M. Chittaranjan, C. Ravi Kumar Reddy, K. Kowshik

Abstract*: Installation of stone column is one of the effective solutions to improve the engineering properties of the soft ground. This paper investigates the performance of stone column treated ground beneath the embankment by using finite element method (FEM) using PLAXIS 2D. The consolidation effect of soft soil due to inclusions of stone columns has been addressed in this study. Numerical predictions are analyzed in terms of settlements, increments in vertical effective stresses, consolidation time and excess pore pressures. Firstly, the effectiveness of the use of stone column is studied. Afterwards, a parametric study has been performed to study the influence on height of the clay layer, height of the embankment fill, length variation in stone columns and the area replacement ratio. Furthermore, due to the installation of stone columns, improved effective stresses in the influence zone have been plotted.

Keywords: Soft Soil; Stone column; Effective Stress; Settlements; PLAXIS 8.6(2D)

I. INTRODUCTION

1.1 General: The consolidation settlement due to high compressible soft clays creates a lot of problems in the foundation engineering. These characteristics such as high compressibility and low shear strength and low permeability may result in excessive settlements in the foundation soil as well as responsible for prolonged primary consolidation settlements.

To shorten this consolidation time, stone columns are installed along with preloading by embankment and surcharge. When stone columns are used, the consolidation settlements will come down. Thus, the installation of stone columns in clay reduces reduce the time to attain the desired amount of consolidation and sufficient shear strength to the foundation. Therefore, the purpose of stone columns is to reduce the foundation settlement, rapid construction of the embankment and one can achieve the desired shear strength based on the project requirement.

Experimental and numerical modeling of consolidation settlements and the shear strength improvement by the installation of stone column supported embankment were analyzed by several researchers. In recent years, the reinforcement of weak foundation soils with stone columns has expanded a great deal around the world, which allows increase in stability, reduction of settlements, greater speed of execution and reduced cost. The lateral pressure and shear stress can be exerted on surrounding clays during the installation of stone columns. Thus accelerate the construction time and improving the load bearing capacity of the foundation soil. The application of stone columns is widely used in construction of storage tanks, earthen embankments, raft foundations, etc.

1.2 Length Reduction Technique

In this study, an attempt has been made by reducing the adjacent length of the stone column by 0, 10, and 20% respectively. Numerical studies have been performed on length reduction of adjacent stone column also variation in the stone column diameter, embankment height and the thickness of the foundation soil. Finally, in this technique is to ensure the acceleration of the construction time of normally consolidated soft clay layers as well as to increase the undrained shear strength of the foundation soil.

1.3 Objective of the study & Definitive objectives

The main aim of this study is accelerate the construction of high embankments on soft soils for infrastructure development.

Definitive objectives

- Improvement of consolidation behaviour of the soft ground by introducing stone column.
- Improvement of stiffness of the soft ground.
- To attempt a new length reduction technique to minimise project cost.

1.4 Problems associated with soft soils

The construction industry is constantly facing challenges with soft soil deposits. Soft clay deposits have a very low bearing capacity, highly compressible and excessive settlement characteristics. The strength development of soft soil is time dependent. These clay deposits are commonly widespread in the coastal areas and major river valleys, of varying thickness, ranging from 5m to 30m. (Bujang B. K Huat). Surface loadings in the form of embankments inevitably results in large settlements.

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II. METHODOLOGY

2.1 General: In this chapter, the designs of stone columns with various conditions have been discussed. The data obtained from this chapter is important in numerical simulations as well as theoretical predictions. Finite Element Software Plaxis-2D has been used in this study to analyze the numerical predictions in terms of

- Settlements
- Increment in vertical effective stresses
- Consolidation time
- Excess pore pressures

2.2 Assumptions in the problem

- Considered a four lane road embankment which is 23m wide.
- Width of the embankment is 30m (as it is symmetric, 15m width has been considered in the model).
- Height of the embankment 4m and 6m.
- Slope of the embankment is 1V to 2H (1:2).
- Stone Column diameter 0.3m and 0.6m.
- C/c spacing between two stone columns 2m and 3m respectively.
- Length reduction in the adjacent stone column in the model is 0, 10 and 20% respectively.

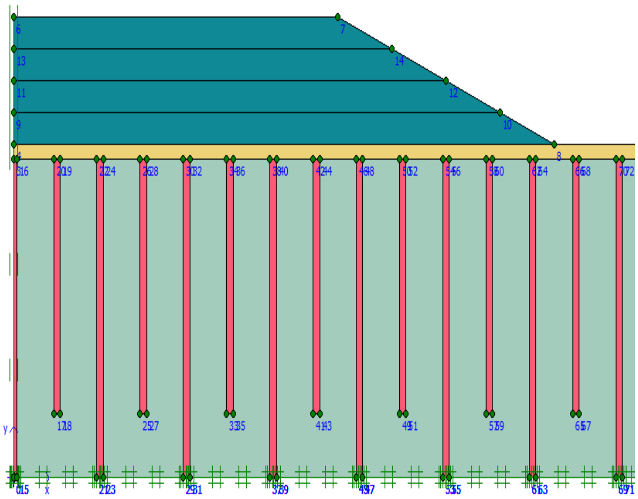

Fig.1 Installation of stones column in soft clay foundation (Plaxis model)

2.3 Parametric studies

To study the performance of stone column treated soft ground, a series of parametric studies have been carried out and stated below Table.1. One can see the typical arrangement of the model geometry in the above Fig.1. Further, a series of parametric studies have been conducted in order to verify the following below conditions.

(a) Change in height of the clay layer
(b) Height of the embankment fill
(c) Length variation in stone column,

Numerical predictions are analyzed in terms of

(d) Settlements
(e) Excess pore water pressure
(f)Consolidation time.

Table.1: Parametric study for numerical simulations

S. No	Stone Column Dia (m)	Spacing (m)	Height of the Embankment (m)	Length Reduction in Adjacent Stone Column (%)
1	0.3	2	4	0
2				10
3				20
4			6	0
5				10
6				20
7		3	4	0
8				10
9				20
10			6	0
11				10
12				20
13	0.6	2	4	0
14				10
15				20
16			6	0
17				10
18				20
19		3	4	0
20				10
21				20
22			6	0
23				10
24				20
25	NA	NA	4	NA
26	NA	NA	6	NA

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2.4 Numerical Modeling

Numerical modeling methods help to improve the reliability on engineering design and provide economically optimized design. Among the available methods, finite element analysis (FEA) or finite element method (FEM) is the most popular one. The basic idea of finite element method is to divide the structure or region into large number of finite elements which are interconnected by nodes, analyze each element in local co-ordinate system and combine the results in global co-ordinate system to get the unknown variable for the entire system.

In this study, series of numerical simulations are required to perform to understand the behavior of the stone column treated ground. It is difficult to develop analytical models with various lengths and diameters of stone columns and different height of the embankment and soft clay layer (foundation soil). Hence, numerical study is undertaken to

model the current problem. Mohr Coulomb model and Linear Elastic soil models. The details of material properties are given in Table.2 and methods to solve the numerical analysis has been discussed right after the material models which includes boundary conditions, meshing, water pressure generation, initial stresses generation and consolidation calculation method.

Table.2: Material properties used in the numerical analysis

Material	Young's Modulus(E, kPa)	Poisson's ratio μ	Cohesion (kPa)	Friction angle (Ø°)	Density
Embankment fill	15000	0.3	3	33	18
Sand blanket	7000	0.3	1	28	16
Soft Clay	3000	0.3	10	1	17
Stone column	60000	0.25	15	40	19

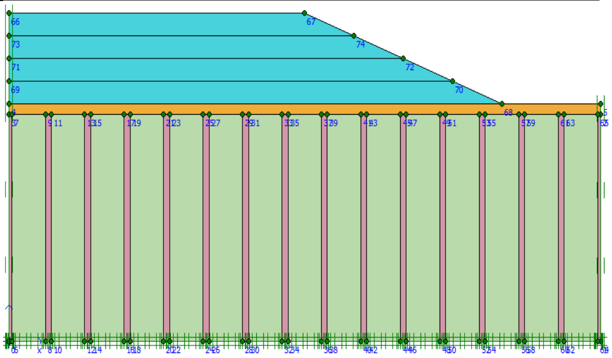

Fig.2 embankment with boundary conditions

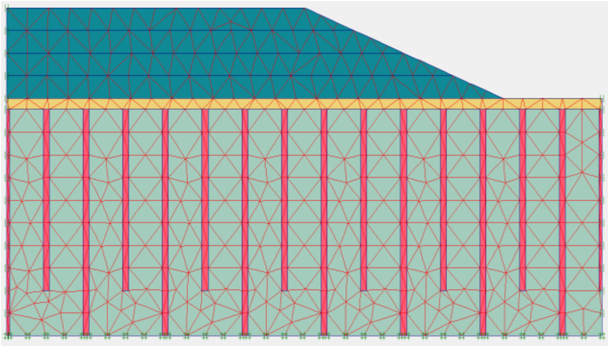

Fig.3 Finite element mesh by using PLAXIS-2D

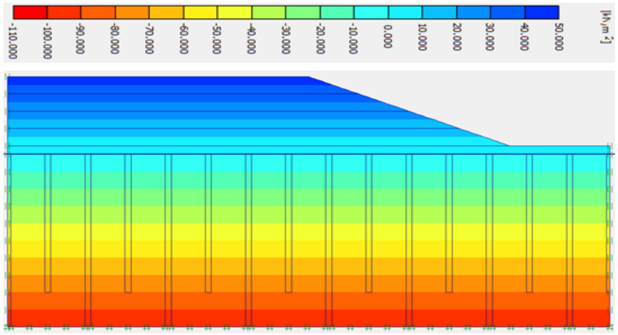

Fig.4 Generation of water pressures in PLAXIS-2D Software

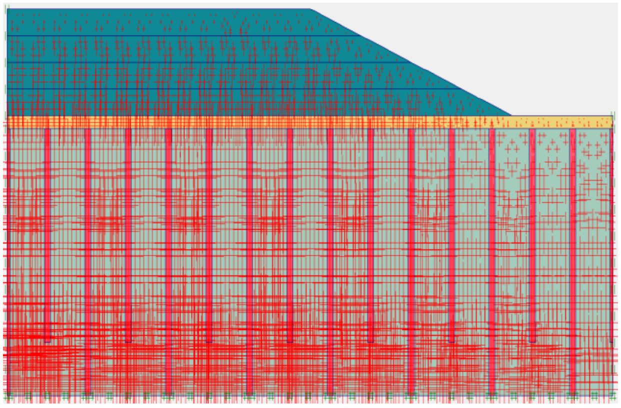

Fig.5 A typical figure of initial stresses generation in the PLAXIS-2D Software

III. RESULTS & DISCUSSIONS

3.1 Analysis of Results

3.1.1. Variation of excess pore water pressure

The indication of gaining shear strength and increased consolidation settlements are due to expulsion of excess pore water pressure. More the expulsion of pore water pressure generated during the construction of embankment implies excessive settlements in a given period of time. The typical variations of excess pore water pressure with time for different conditions have been observed from Fig.6 to Fig.13. Below Figures shows the change in excess pore water pressures due to staged construction loading.

High excess pore water pressures are noticed in untreated and comparatively lesser in stone column improved ground at different stages.

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With increase in excess pore water pressure; there is a reduction in the undrained shear strength of the soft ground which in turn brings down the stability of the system. Hence, it is required to further increase the consolidation time to make the excess pore water pressures to zero which leads to an uneconomical solution. Fig.9 shows the maximum pore pressures (0.9 kPa) compare with remaining condition because it has less stone column diameter (0.3) with more spacing (3m). One can observe the Fig.13 producing very minimal pore pressures in the foundation soil and it doesn’t create any problem by means of shear failure.

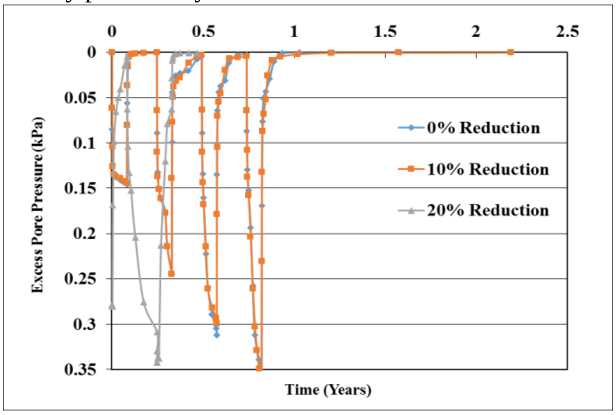

Fig.6 Time Vs Excess PP for Dia 0.3, Spacing 2m and Emb. Height 4m

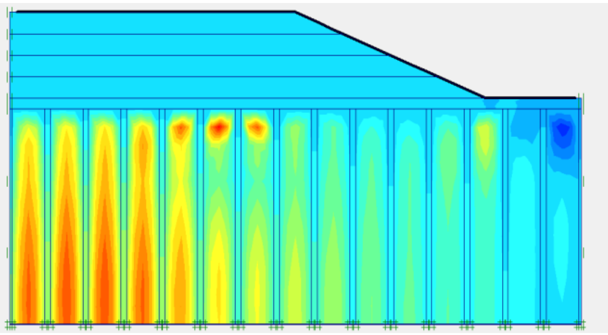

Fig.7 Typical excess pore water pressure generation in the soft clay foundation

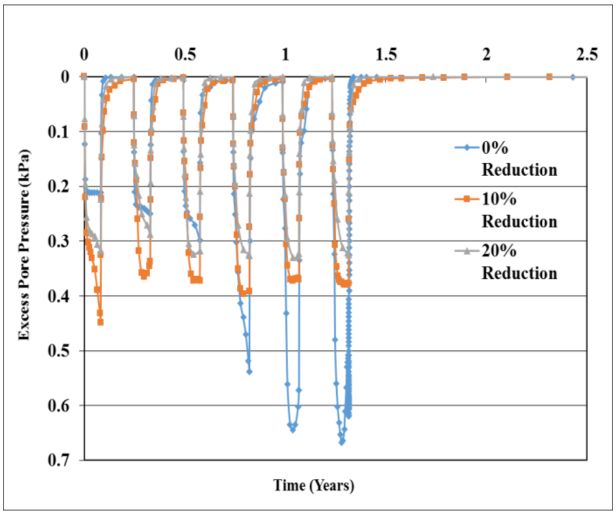

Fig.8 Time Vs Excess PP for Dia 0.3, Spacing 2m and Emb. Height 6m

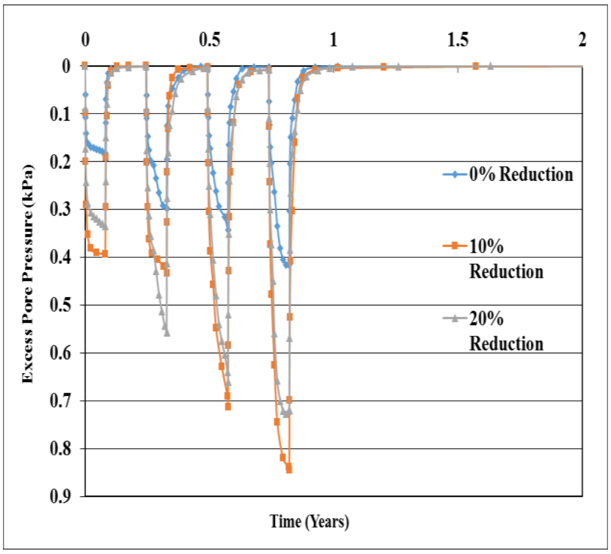

Fig.9 Time Vs Excess PP for Dia 0.3, Spacing 3m and Emb. Height 4m

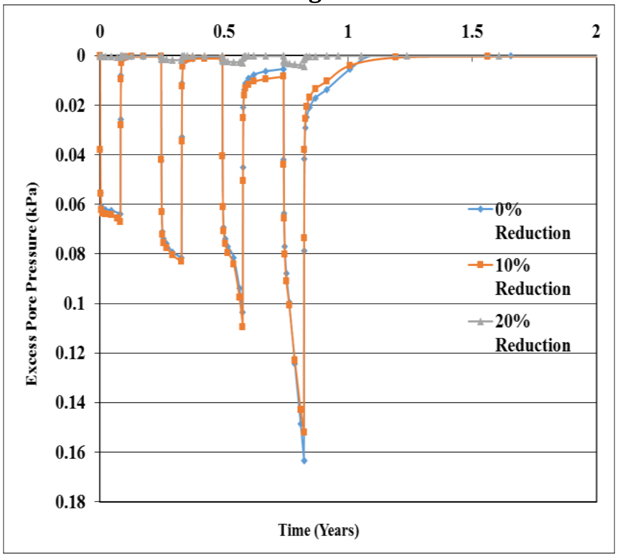

Fig.10 Time Vs Excess PP for Dia 0.6, Spacing 2m and Emb. Height 4m

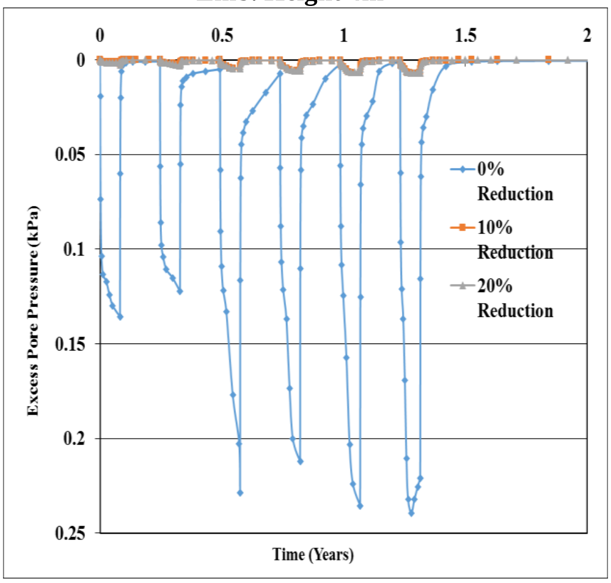

Fig.11 Time Vs Excess PP for Dia 0.6, Spacing 2m and Emb. Height 6m

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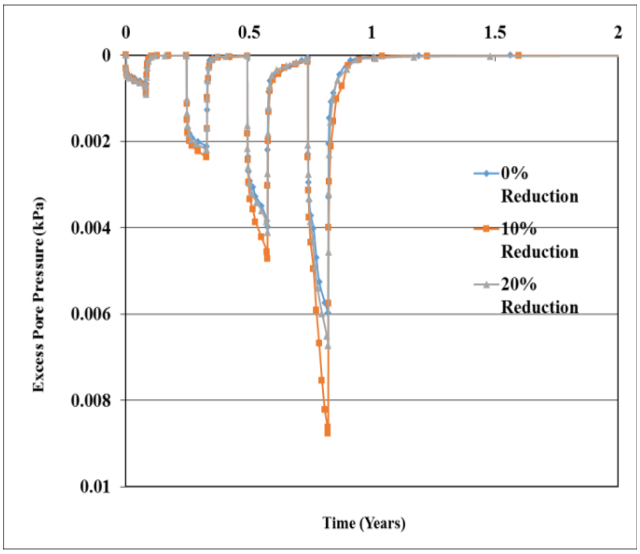

Fig.12 Time Vs Excess PP for Dia 0.6, Spacing 3m and Emb. Height 4m

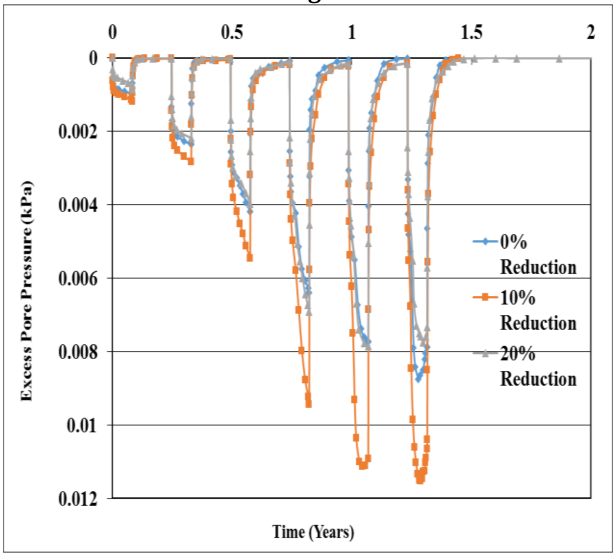

Fig.13 Time Vs Excess PP for Dia 0.6, Spacing 3m and Emb. Height 6m

3.1.2 Settlement analysis:

Consolidation settlement is a time related process of reduction in volume due to the expulsion of water. The vertical effective stresses will be increased in this process thus the shear strength will improve ultimately. Consolidation settlements have been measured with respect to time in each independent case. Constant settlements have been observed after the consolidation period and plotted for each case and presented in the below figures.

Settlement analysis for the embankment construction has been performed in this study. As explained in the previous, the embankment construction has been performed in staged manner. Deformation patterns have been shown in the below Fig.14 to Fig.20. Large deformations have been observed in the fig.15 as it is having lesser stone column diameter (0.3m) and more c/c spacing (3m). Minimal displacements have been noticed in the Fig.17 because of the optimum diameter and spacing. Length reduction of stone columns affected in the ultimate displacements and the results are tabulated in the below Table.3

Table.3 Parametric study results for Ultimate Displacements

S. No	Stone Column Dia (m)	Spacing (m)	Height of the Embankment (m)	Length Reduction in Adjacent Stone Column (%)	Ultimate Displacement (mm)
1	0.3	2	4	0	93
2				10	109
3				20	122
4			6	0	295
5				10	310
6				20	489
7		3	4	0	128
8				10	167
9				20	171
10			6	0	278
11				10	315
12				20	502
13	0.6	2	4	0	52
14				10	60
15				20	65
16			6	0	161
17				10	252
18				20	299
19		3	4	0	77
20				10	94
21				20	101
22			6	0	201
23				10	250
24				20	283

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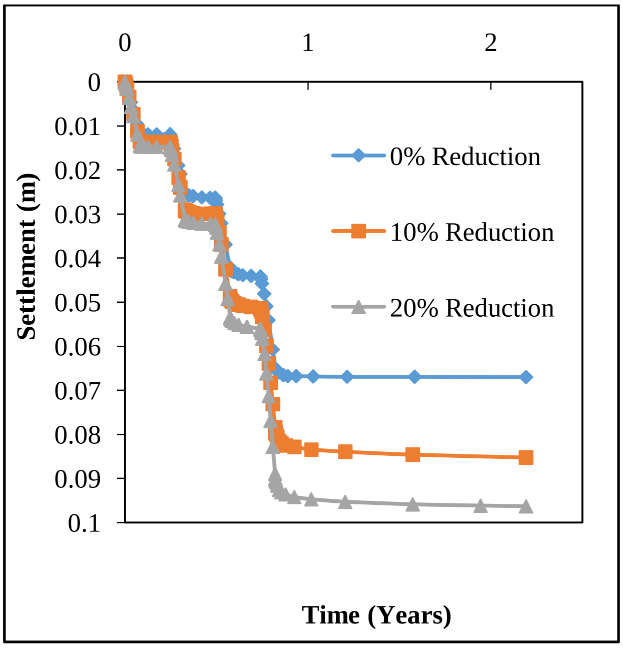

Fig.14 Time Vs Settlement for Dia 0.3, Spacing 2m and Emb. Height 4m

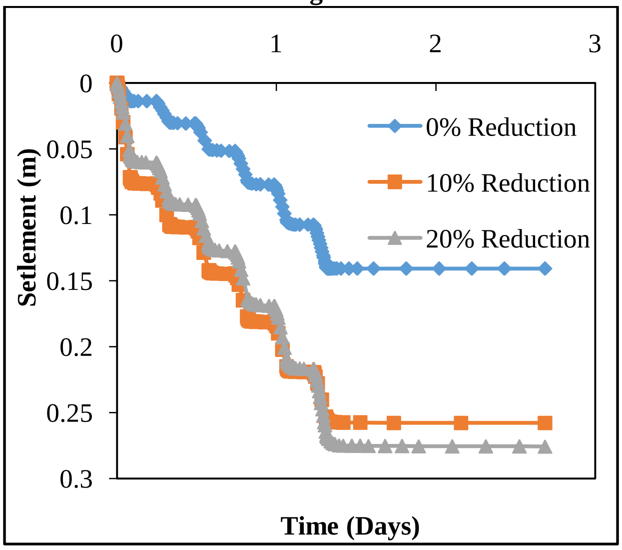

Fig.15 Time Vs Settlement for Dia 0.3, Spacing 2m and Emb. Height 6m

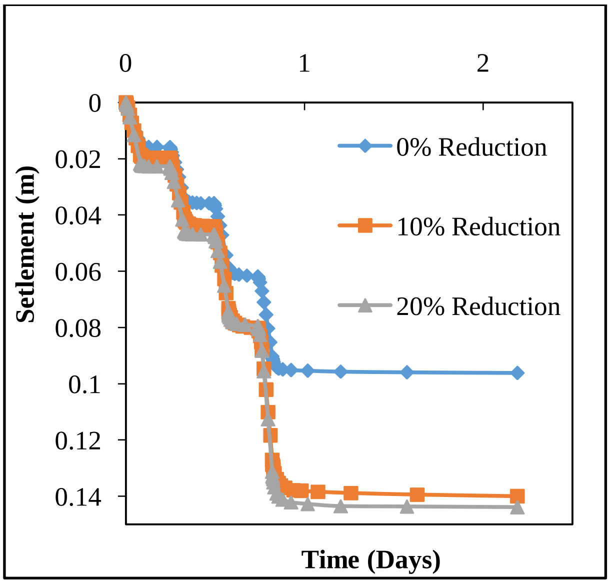

Fig.16 Time Vs Settlement for Dia 0.3, Spacing 3m and Emb. Height 4m

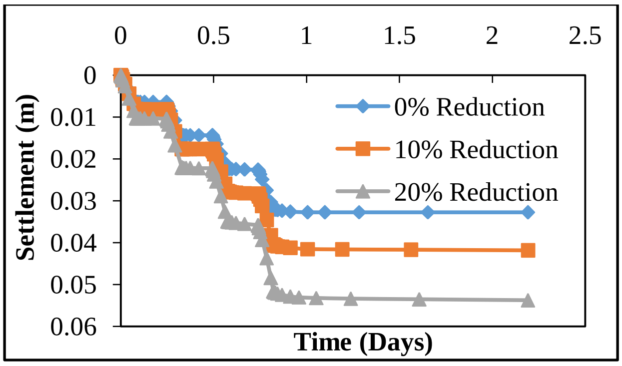

Fig.17 Time Vs Settlement for Dia 0.6, Spacing 2m and Emb. Height 4m

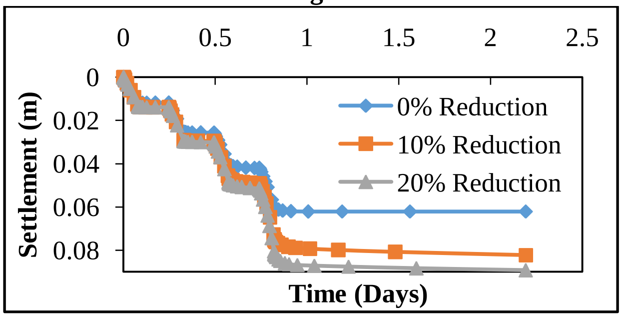

Fig.18 Time Vs Settlement for Dia 0.6, Spacing 2m and Emb. Height 6m

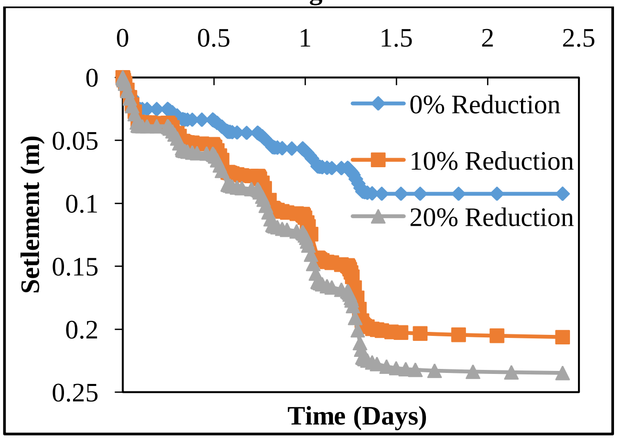

Fig.19 Time Vs Settlement for Dia 0.6, Spacing 3m and Emb. Height 4m

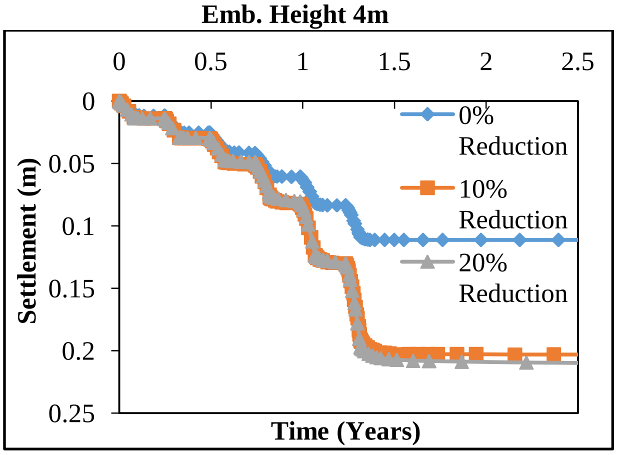

Fig.20 Time Vs Settlement for Dia 0.6, Spacing 3m and Emb. Height 6m

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IV. CONCLUSIONS

Table.4 Conclusion table

Column Dia (m)	C/C Spacing (m)	Height of the embankment (m)	Length Reduction (%)	Settlements (mm)	Consolidation Time (Days)
0.6	2	4	0	52	760
			10	60	805
			20	65	836
	3		0	77	780
			10	94	873
			20	101	889

Conclusions have been drawn from all the individual cases and tabulated in the below Table.4.There are six different optimum design cases have been noticed among all. In these cases, the minimum and the maximum settlements have been observed as 52mm and 101mm respectively and these are in the allowable range. Stone column diameter of 0.6m produces the better results when compared to the 0.3m diameter stone columns. The optimum c/c spacing has been observed as 2m and 3m respectively and same has been listed in the above Table.3 and the optimum height of the embankment has been observed as 4m in height.

One can adopt these combinations in soft clay foundation and design the stone columns for the rapid construction of the embankments with varying heights 4m and 6m respectively.

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