Compressibility Studies on Cochin Marine Clay Stabilised with Fly Ash and Lime Columnar Inclusions

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Abstract. The study focuses on the use of lime, fly ash and combination of these materials as columnar inclusion for improving the strength and compressibility characteristics of soft Cochin marine clay. Large scale consolidation tank was used to study compressibility characteristics A group of five columns of different materials (lime, fly ash and a combination of both) were installed in the tank filled with marine clay in its natural moisture content. The consolidation test was continued till the settlement rate reached a value less than 1 mm/day for the different applied pressures. It was observed that clay alone took 91 days to reach target settlement, whereas the lime column took 29 days, fly ash column took 51 days and 1:1 lime – fly ash column took 39 days. The shear strength of the clay increased with the installation of the columns of different materials

Keywords: Large scale consolidation, lime column; fly-ash column; lime – fly ash column.

1. Introduction

Soft clays of low strength and high compressibility are located along the coastal and offshore areas and they cause several foundation problems for the structures founded in these deposits. Construction in such soils requires ground improvement techniques. Use of flyash and lime for ground improvement is a widely researched topic. Addition of flyash to soil improves strength and decreases volume change behavior of expansive soils. These values are further decreased by addition of small percentage of lime [10]. Further, reduce plasticity and linear shrinkage of expansive soils [5, 4] with nearly 6% lime added to soil giving optimum results in terms of strength, density and plasticity [9]. Fly ash, when compacted in form of columns, decreases heave on clay beds [16]. Compacted Lime–Soil columns exhibit a stiffer and stronger response compared to conventional stone columns installed in soft soils and its performance is remarkably enhanced by increasing the area ratio [13]. Also, their group efficiency decreases with increase in the number of columns for both lime and stone columns [1]. On addition of fly ash and lime, the montmorillonite structure of clays were found to be broken and pozzolanic action dominated over cation exchange capacity [17]. Lime fly ash column effectively improves the physical and engineering characteristics of Cochin marine clay and preloading technique offers better improvement in properties compared to compacted lime fly ash columns [11]. In Kuttanadu clays, shear strength, plastic limit and shrinkage limit are higher near lime columns and increases on curing [18], whereas, moisture content and liquid limit decreases, permeability increases initially and then decreases.

Behavior of stone columns are affected by spacing, shear strength of clay, moisture content, diameter etc based on experimental and theoretical evaluation [3] and load settlement behavior may be taken as linear and maximum bulging occurs at 0.5 to 1 times column diameter from top. Geosynthetic encasement of stone columns increases their load carrying capacity further [11] by increasing its lateral confinement. Stone columns installed in soft clays provide moderate increase in load carrying capacity, accelerates consolidation settlement and thus reduces post construction settlement [7]. In soft or loose layered soils, load carrying capacity of stone column-improved soils increases with diameter of columns [6]. However, subsoil investigation from bore-holes should be supplemented by insitu test results before designing stone columns [8].

Numerical modelling techniques using Finite Element Method (FEM) and Finite Difference Method (FDM) are highly effective in understanding the long term field performance of soils improved with columns. Studies using FLAC, an FDM package a simple rectangular grid has been used to represent the foundation soil, modeled in plane strain [20)] and interactions between the individual stone columns, the loaded area and the surrounding soil can be understood as the behavior of `piles' with non-linear, sand-like axial stiffness properties. In FEM, Mohr – Coulomb criterion is employed for drained analysis of clay, sand and stone and analysis is being carried out using a unit cell concept i.e., deformations in the clay are restrained within unit cell [2]. From FEM analysis of geogrid encased stone columns [12], stone column derives its resistance by its bulging over a length of 4d to 6d under the load with maximum bulging at the depth around 2d and the column material offers passive resistance against bulging. From FEM analysis of fully drained stone columns in soft clays, [19], the major foundation parameters affecting their group response were identified as area ratio, normalized column length, Young’s modulus of column, over consolidation ratio, initial geostatic stresses, and clayey soil parameters. From numerical analysis [14], assumptions, procedures and results of behaviour of non-encased versus geogrid encased stone column in soft clay with the aid of finite element software, PLAXIS V8, a reasonable agreement obtained between the experimental investigation and the finite element method. Compacted Lime-Well-graded Soil (CL-WS) columns increase the load carrying capacity of soft soils and reduce the settlement [13], but FEM results indicate influence of model size on the stiffness of the specimens. However, for specimens containing columns with diameter greater than 100 mm, the variations of stiffness become negligible and hence the results can be used to extrapolate and predict the full size behavior of these columns.

The paper concentrates in investigating consolidation behavior of lime columns and fly ash columns in soft marine clays. Large laboratory consolidation tests and numerical analysis was carried out to study the ground improvement achieved.

2. Materials

The materials used for the study are marine clay, lime, class F fly ash and uniformly graded fine sand. Marine clay used in the study was collected from Vallarpadam, in Cochin on the Western coast of India. For uniformity samples were pooled together and mixed thoroughly into a uniform mass and preserved in polythene bags to maintain the water content. The properties of marine clay are presented in Table 2. The sand used in the study was obtained from the Periyar River basin. This sand was sieved using IS sieve 2mm and 425µ and the medium size fraction of the river sand thus obtained was taken for the study. The properties of the sand used in the study are given in table 1. The commercially available superior grade quick lime was used to prepare lime column. The specific gravity of lime used in the study is 2.36. ASTM C618 specified two categories of fly ash, Class C and Class F. In the present study Class F fly ash collected from the Hindustan Newsprint Ltd, Vellore, Kottayam. The fly ash had a natural water content of 14 % and its specific gravity is 2.26. Figure 1 shows the XRD pattern of Class F fly ash used in the study.

Table 1 Properties of Sand used in the study

Properties	Values
Specific gravity	2.57
Effective size,D10 (mm)	0.52
D30 (mm)	0.72
D60 (mm)	1.1
Uniformity coefficient, Cu	2.11
Coefficient of curvature, Cc	0.906
IS Classification	SP

Table 2 Properties of Marine clay used in the study

Properties	Values
Natural moisture content (%)	127
Specific gravity	2.65
Liquid Limit (%)	135
Plastic Limit (%)	58
Shrinkage Limit (%)	16
Plasticity Index (%)	77
Particle size distribution	
Clay size (<0.002mm) (%)	60
Silt size (0.002mm-0.075mm) (%)	35
Sand size (>.075mm) (%)	5
IS Classification	MH

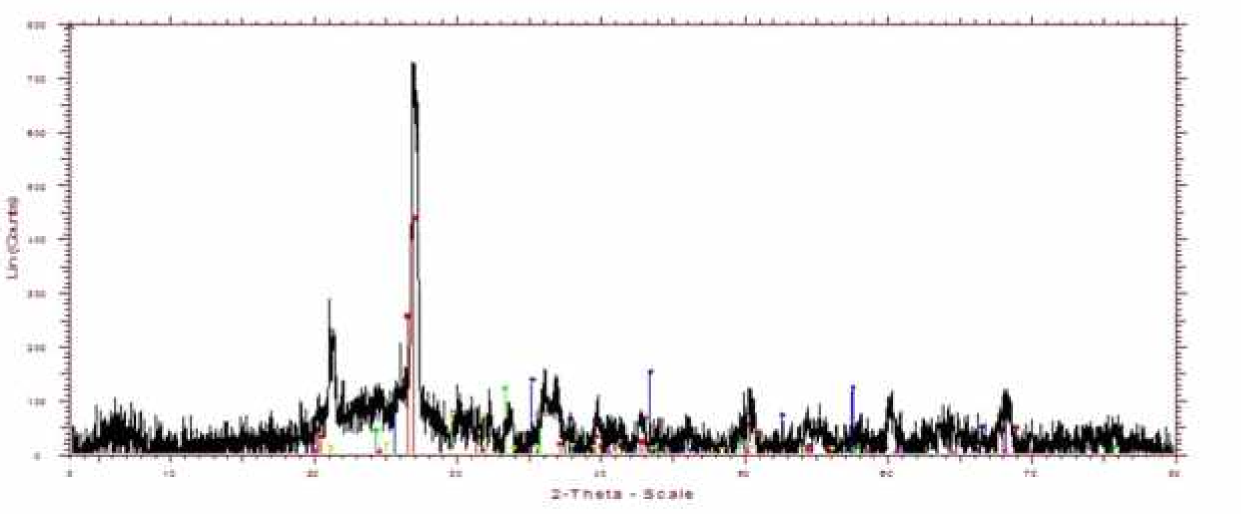

Figure 1 XRD pattern of Class F fly ash used in the study

3. Experimental Programme

Consolidation study of columnar inclusions on clay bed can’t be conducted in lab oedometer test, so large scale tanks were fabricated. The following section gives in detail the experimental set-up. The setup consists of a model tank of height 700mm, and diameter 400 mm. The model tank boundary was determined on the basis of criterion that induced stresses should be insignificant at the tank boundaries. The load is applied to the clay bed by means of a loading frame using the principal of lever arm. The bottom portion of the cylinder has holes and the upper portion of the clay bed consists of a porous plate to allow two way drainage and thus simulate the field condition. The apparatus has a loading capacity of 35 kPa. The loading frame is considered as a cantilever beam and the load transferred to the cylinder calculated as : X = 2.4W/05. Figure 2 shows the schematic diagram of experimental test arrangement.

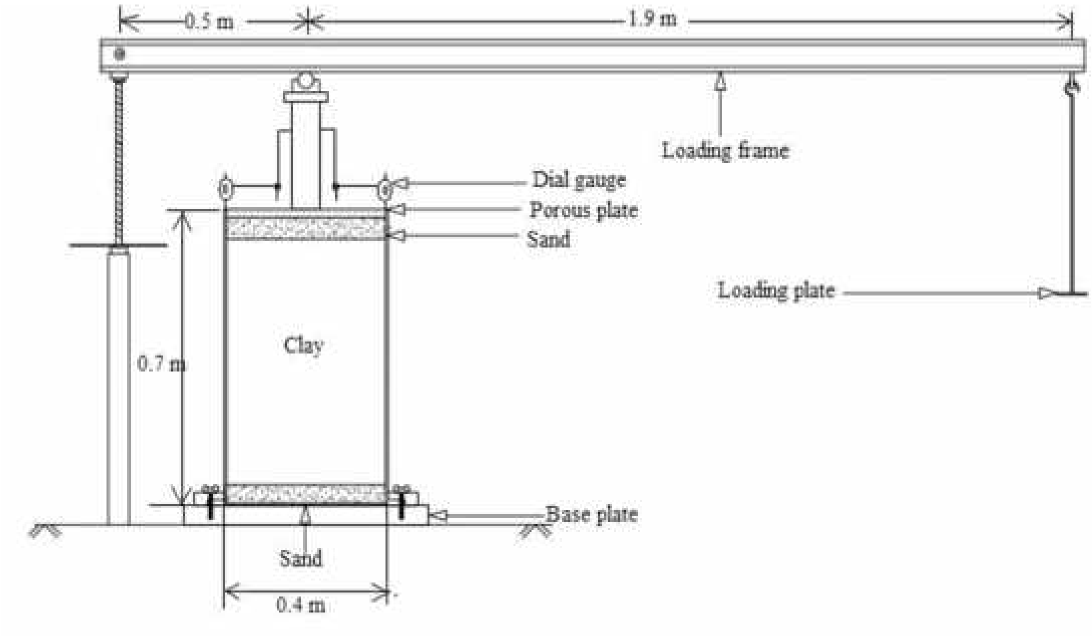

Figure 2 Arrangement of column in the model tank

A group of 5 column with diameter 40 mm, length 580 mm and spacing 120 mm were installed in the model tank. The bottom of the tank was provided with a 50 mm thick sand filter layer with drainage outlets. Thin open ended PVC pipe of diameter 4 cm was placed inside the tank with the help of guards and the clay was filled in the tank in between the PVC pipes with uniform compaction to achieve a density of 15 kN/m3. Then the column materials were filled into the PVC pipes in layers of 50mm each giving uniform compaction to each layer using metallic rods. Casing pipe is raised in stages ensuring minimum 5mm penetration below the top level of the placed column material. Drainage was permitted at the top of the clay bed by placing 50mm thick sand layer and above that a porous metal plate. After preparing the column, the applied pressure v/s deformation behavior of column/ treated soil will be studied by applying vertical load in a loading frame. The experiment was continued till the settlement rate reaches a value less than 1mm/day for different applied pressure (12.5kN/m^2, 16.8kN/m^2,21.04 kN/m^2, 29.63 kN/m^2, 46.8 kN/m^2). After consolidation, the clay surrounding the column were collected to study the strength characteristics. Figure 3 shows the arrangement of column in the model tank.

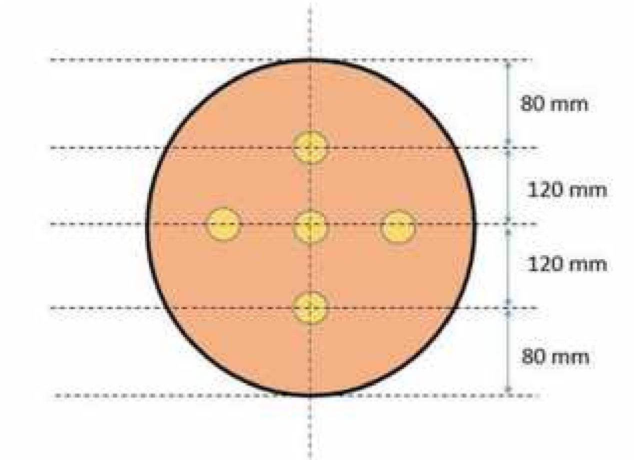

Figure 3 Arrangement of column in the model tank

Lime columns and Fly ash columns were installed in the test tank as explained above. Lime powder and flyash passing through 425µ were filled and compacted to achieve a density of 10.4 kN/m3 .

4. Numerical Modelling

An axisymmetric analysis was carried out using Mohr-Coulomb's criterion for clay and other materials. The geometry model of tank with group of column is shown in figure 4. After drawing the geometry of the model properties were assigned according to the study. Next step was to give the boundary condition and the load to the column. Then the meshing was done. The mesh was refined at all the column portion. After the mesh generation, next step was staged construction and in that step the calculation has been carried out in 5 phases, i.e.; initial phase, phase 1 and phase 2, phase 3 and phase 4. In the initial phase the whole cylindrical model has the soft clay properties and other particulars like load and the column cluster were deactivated. Then a pre-consolidation pressure of 10 kN/m2 were given as two stages in phase 1 and phase 2 with a time interval of 25 days. In phase 3 the properties of column material were assigned to the column cluster. In the 4th phase the load system were activated. Points or the curve were selected and proceeded to the calculation stage.

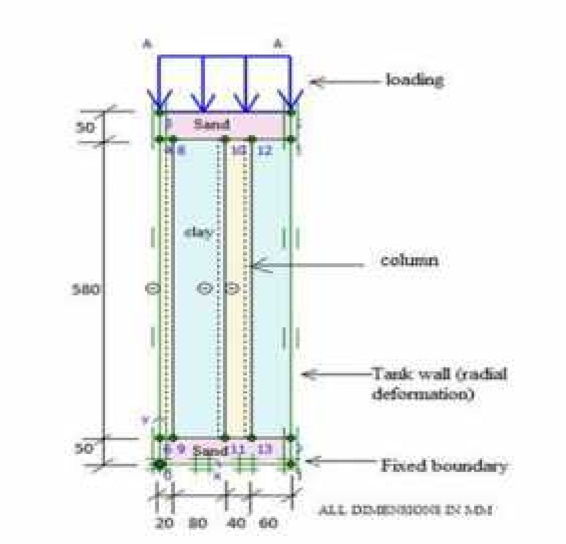

Figure 4 Geometry model of tank with column

5. Results and Discussion

Consolidation tests were performed on models with only clay, group of lime column, fly ash column and 1:1 lime- fly ash column in the model tank. In order to have a settlement rate less than 1mm/day for five different applied pressures (12.5kN/m2, 16.8kN/m2,21.04 kN/m2, 29.63 kN/m2, 46.8 kN/m2) the clay alone model in experimental set up took 91 days where as for the lime column installed in the tank took approximately 29 days, fly ash column took 51 days and lime – fly ash column took 39 days. From the obtained results, for the same applied pressure, the variation in time taken to have the same amount of settlement for only clay, group of lime column, fly ash column and lime fly ash column are shown in table 4.1. Table 4.2, 4.3 and 4.4 shows the percentage reduction in time for lime, fly ash and 1: 1 lime-fly ash column.

Table 3 Variation in time taken to reach same settlement under different applied pressure

Applied Pressure (kPa)	Time taken in days						
	Clay alone	Lime Column	Fly ash column	1:1 lime-Fly ash	Lime Column - % increase	Fly ash column - % increase	1:1 lime-Fly ash - % increase
12.5	10	5	8	6	30	20	40
16.8	22	13	16	13	41	28	41
21.04	44	16	27	17	64	39	62
29.63	67	21	39	28	69	42	59
46.81	86	29	51	39	67	41	66

From the data given above it is clearly seen that the rate of consolidation is more when lime column installed in the clay model followed by 1:1 lime – fly ash column and fly ash column.

For the same applied pressure of 25 kPa, the value of coefficient of consolidation of clay in large scale consolidation test tank is 3.65×10-4 cm2/sec. The value of coefficient of consolidation increased to 6.74×10-4 cm2/sec when lime column installed in the model test tank and 6.01×10-4 cm2/sec for 1:1 lime – fly ash column and 5.38x10-4 cm2/sec for fly ash columns. The value of compression index (Cc) for clay alone is 0.857 and this value decreased to 0.687 when lime column installed in the model test tank and 0.744 for 1:1 lime – fly ash column and 0.755 for fly ash columns.

Thus it can be inferred that installation of columns in the clay bed accelerates the rate of consolidation. Also it can be observed that of all the columnar materials used in the study, lime gave better compressibility characteristics.

Table 4 Consolidation characteristics of clay after installation of columns

Combination	Compression Index (Cc)	Coefficient of consolidation (Cv - cm^2 /sec)
Clay alone	0.859	3.65×10^{-4}
Lime column	0.687	6.74×10^{-4}
Fly ash column	0.7x55	5.38×10^{-4}
1:1 lime-fly ash column	0.744	6.01×10^{-4}

Laboratory Vane shear test were conducted on the test bed of the different combination of materials before and after consolidation. Shear strength of the marine clay used in the study is 6.639 kPa. This value increased to 14.32 kPa after the consolidation for 91 days without any columnar inclusions. When columns were installed in the model test tank, the undrained shear strength value increased to 18.31 kPa in case of lime column, 32.01 kPa for flyash column and 23.47 kPa for 1:1 lime – flyash column. Thus it can be inferred that installation of columns in the clay bed increased the undrained shear strength of soil.

Experimental results were used for the validation of finite element software PLAXIS 2D, for the purpose of cross checking the set of results of only clay in the model tank and group of 5 columns of lime, fly ash and their combination. The dimension of the finite element model has been kept as the same as that of the experimental model. The time- settlement plot of the only clay obtained from the experimental observations matches well with that obtained from PLAXIS analysis. Whereas the time –settlement curve for group of column obtained from PLAXIS results shows a variation from that of the experimental results in higher applied pressure. For the same settlement, for an applied pressure of 46.8 kN/m^2 the results from PLAXIS shows 10-12 days more time as that obtained from the experimental results for lime column, 20-25 days more in case of flyash column and 10-15 days more in the case of 1:1 lime – fly ash column.

6. Conclusions

For the same applied pressure of 25 kPa, the value of coefficient of consolidation (Cv) of clay in large scale consolidation test tank is 3.65×10-4 cm^2/sec. The value of Cv increased to 6.74×10-4 cm^2/sec when lime column installed and 6.01×10-4 cm^2/sec for 1:1 lime – fly ash column and 5.38x10-4 cm^2/sec for fly ash columns. The Cc value for clay alone is 0.857 and this value decreased to 0.687 when lime column installed and 0.744 for 1:1 lime – fly ash column and 0.755 for fly ash columns.

Installation of columns in the clay bed accelerates the rate of consolidation and of all the columns used in the study, installation of lime column gave better compressibility characteristics. Lime column gave better drainage path compared to fly ash columns based on experimental results. However all the combinations of columns provided better drainage path compared to clay only condition.

Undrained Shear strength of the marine clay used in the study is 6.639 kPa. This value increases to 14.32 kPa after the consolidation without any columnar inclusions. When column were installed in the model test tank, the shear strength value increases and it becomes 18.31 kPa in case of lime column, 32.01 kPa for fly ash column and 23.47 kPa for 1:1 lime – fly ash column.

The rate of increase in undrained shear strength of the clay bed with fly ash columns showed maximum increase of 79%. Considering the strength criteria, fly ash columns perform better than others.

In addition to the environmental benefits achieved through the use of fly ash, it has the lowest embodied CO_2 content of 4 KgCO2/ton compared with cement (930 $KgCO_2$/ton) and limestone 32(Kg CO_2/ton) which makes them suitable for stabilizing purposes.

Experimental results were used to compare the results from the finite element software PLAXIS 2D. The time- settlement plot of the only clay obtained from the experimental observations matches well with that obtained from PLAXIS analysis.

The time –settlement curve for group of column obtained from PLAXIS results showed a variation from that of the experimental results in higher applied pressure. For the same settlement, for an applied pressure of 46.8 kN/m2 the results from PLAXIS shows 10-12 days more time as that obtained from the experimental results for lime column, 20-25 days more in case of flyash column and 10-15 days more in the case of 1:1 lime – fly ash column.

Numerical study shows that installation of single column in the clay bed takes 20 - 35 days more than that of group of column for all materials to achieve a particular settlement of 20mm.

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