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In-Situ Study on Improvement of Soft Ground Using Stone Columns For Railway Embankment

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Abstract. The authors through this paper intend to introduce the non-vibro technique of ground improvement by stone column, being used for the first time in India under the Western Dedicated Freight Corridor in Mumbai area. New 2x25 KV double line dedicated freight corridor tracks, capable of carrying 32.5-ton axle load are proposed to be built on this stretch. Non-Vibro Displacement Stone Columns of 900 mm diameter were installed to improve the safe bearing capacity of the soft ground to take the loading of Dedicated Freight Corridor Railway embankment. Vertical footing load tests on single and three column groups were conducted to assess the improvement in the sub-surface condition after installation of stone columns. This paper describes load tests conducted on stone columns and analysis of the obtained results. The observed load settlement behaviour of the improved ground has also been presented. Behaviour of single and group of stone columns have been compared and criteria adopted for arriving at desired factor of safety based on the settlement observed, has also been discussed.

Keywords: Stone Columns, Soft Soils, Ground Improvement, Consolidation, Preloading

1 Introduction

Ministry of Railways (Govt. of India) is constructing the highly ambitious 2x25 KV electrified double line Western Dedicated Freight Corridor carrying heavy haul(HH) freight tracks for a length of about 1500 km between Mumbai and Delhi. A stretch of about 100 km in the state of Maharashtra runs parallel and close to the densely worked suburban tracks of Mumbai, along the coastal area. In this stretch, various long patches totalling to around 22km are having marine clay of depths varying from 6m to 19m. The bearing capacity of the soil in these stretches is very less with Standard Penetration Test (SPT) values of 0-5, undrained shear strength less than 25kPa and EV2 (Elastic modulus of 2nd step plate load test) less than

20MPa. The strength of these soils are quite less and need to be improved by suitable method in terms of GE:0014(2009) issued by RDSO.

During initial planning, several methods of ground improvement like stage construction, Sand drains, Wick drains, Geocell, Stone column etc. were evaluated. Taking into consideration, the depth of soft soil, existence of underneath bearing strata, area to be covered, proximity to Indian Railway tracks (limiting large consolidation settlements) and the time period of construction, it was decided to carry out the ground improvement of the patches parallel to the tracks by stone column method.

While looking for the solution to this problem, Non-Vibro Ground Improvement method, as developed and patented by Jaron McMillan of New Zealand, was incorporated in the DFCCIL project for Mumbai area. This non-vibro stone column installation technique implemented first time in India.

2 General Description

2.1 General geology and site conditions

Subsurface Investigation was carried out by conducting SPT tests and Vane Shear tests in boreholes at every 500m interval along the stretch. From the above details, it is clear that soft to very soft marine clay of thickness varying from about 6 to 12.5m is existing at the top followed by weathered to hard rock (BASALT). The standard penetration test (SPT) 'N' value obtained in marine clay strata varies from less than 1 to 4. The average field vane shear strength taken as 20 kN/m^2 in this layer. Laboratory tests on soil samples collected from marine clay strata indicated cohesion value varying from 9 to 15 kN/m^2, liquid limit varies from 53 to 105%, plastic limit varies from 24 to 44% and field moisture content varies from 36 to 117%. Ground water table was very close to the ground level due to its approximity to Arabian Sea.

In order to ascertain the nature of soil in the stretch under consideration, sub-soil investigation was carried out at every 500m on normal formation stretch, one at each minor bridge location and one bore hole at every third pier location for major bridges. In this paper, the example of soil in JNPT area of Navi Mumbai has been considered for elaboration of this non-vibro stone column method.
From the study of these data, the subsurface stratification was identified as –

1. Layer 1: Very Soft Clay (Compressible Layer)
2. Layer 2: Soft Clay (Compressible Layer)
3. Layer 3: Stiff Clay
4. Layer 4: Medium Clay
5. Layer 5: Completely/ Highly/Moderately Weathered Rock (BASALT)

The existing Safe Bearing Capacity (SBC) of the soil was 20kN/m^2 and the expected settlement of the untreated soil for the proposed embankment and rail load was 1000 to 1600 mm. Based on the boreholes, as listed in Table 1, the soil observed at top is soft clay followed by weathered to hard rock. The soil profile is also shown in the Figure 1 below. To determine the in- situ soil strength, Standard penetration test (SPT) at various depths were carried out in each borehole. The observed SPT-N Values are presented in Table 2.

Table 1. Soil profile from DFC CH 2.9 to 3.8 km in various boreholes

Structure	Borehole No.	Chainage	Co-ordinates		R.L. (m)	Borehole Termination Depth (B.G.L.) (m)	Water Level (B.G.L.) (m)
			Northing	Easting			
Minor Bridge 13	BR-13	2+933.07	2091584.965	288217.769	2.729	14.00	1.80
Embankment Fill 3000	BH- 3000	3+000	2091483.362	288469.093	3.692	16.00	1.00
Embankment Fill 3500	BH- 3500	3+500	2091561.773	288947.143	1.812	15.10	0.55
Minor Bridge 15	BR-15	3+562.83	2091591.253	289000.308	1.210	16.50	0.00
Minor Bridge 16	BR-16	3+801.95	2091708.933	289212.535	1.317	12.00	0.00

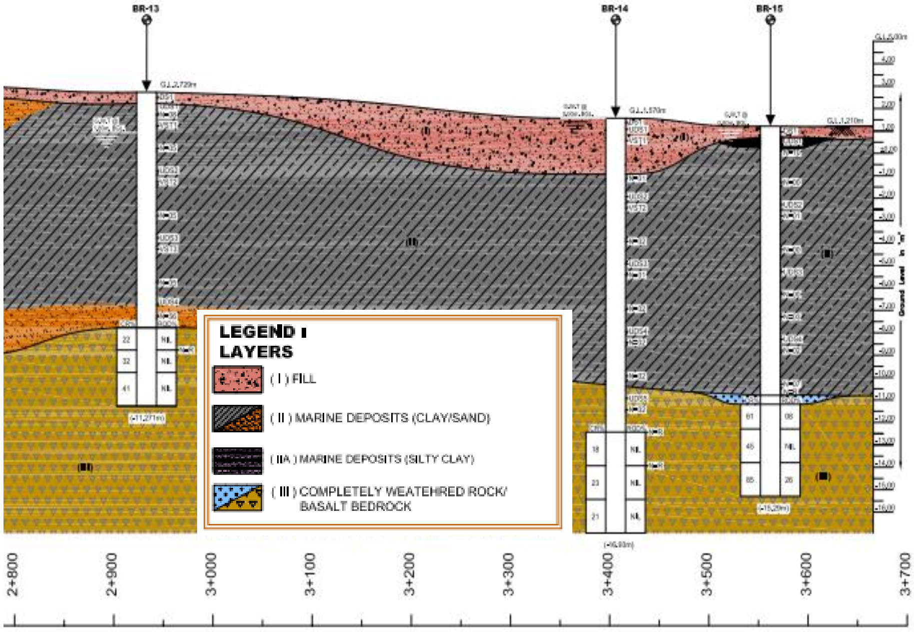

Fig. 1. Profile at DFCCIL Chainage from 2.800km to 3.700 km in JNPT area

Table 2. Field SPT values at various depths in different bore holes

BH No.	BH-13	BH-3000	BH-3500	BH-15	BH-16
Chainage	2933.07	3000	3500	3562.83	3801.95
GL(m)	2.729	3.692	1.812	1.21	1.317
GWT(m)	1.8	1	0.55	0	0
Depth(m)			SPT N - Values		
1.5	8	5	5	10	3
3	5	7	0	0	0
4	-	2	0	1	0
6	5	2	3	0	3
7.5	-	2	3	0	2
9	5	2	3	3	100
10.5	56	5	4	2	100
12	100	15	32	7	100
13.5	100	38	100	100	
15		53	100	100	
16.5		100		100	

3 Design of Stone Column

3.1 General

The non-vibrostone columns are designed using the IS code15284 (Part-1): 2003[9], as being used for the design of column being constructed by the conventional vibroflot method. The spacing of the stone column, as per the design using the codal procedure and the existing soil properties, came out to 2.4m centre to centre, while the diameter as 900mm. The design philosophy and procedure are explained below:

3.2 Design philosophy

The stone column design is performed based on the IS 15284 (Part-1): 2003[9]. The design methodology involving the following steps is briefed in subsequent paras:

a) Identification of Design Engineering properties of soil strata.

b) Basic input for design parameter of stone column (Diameter, spacing, pattern, equivalent diameter and replacement ratio)

c) Design for ultimate load capacity of column
   - Capacity based on bulging of column
   - Surcharge effect
   - Bearing support provided by intervening soil

d) Settlement Analysis

3.3 Design parameters for soil

Design soil parameters are obtained from the factual geotechnical report of the stretch under consideration. The basic design parameters considered for the design are summarized below:

Average Cohesion value = 22.5 kPa and for average SPT N-value = 2

3.4 Design parameters for stone column

Diameter

Depending on soil condition (shear strength), ramming effect and available tool, diameter would be presumed for the analysis. The equipment is able to drill 600mm, 750mm, 900mm and 1200mm dia stone columns. Keeping in view the loading from embankment, effective drainage path for consolidation, number of stone columns from constructability point of view and spacing of stone columns - 900mm diameter stone column is selected.

Pattern

Equilateral triangle pattern has been considered for the stone column arrangement

(Figure 2).

Spacing

Spacing of column (S) is based on loading pattern, column factor, installation technique and settlement tolerance (i.e. 2 to 3 times column diameter) with tributary area (in the form of a hexagon) for column considered 0.866 S^2 for triangular pattern.

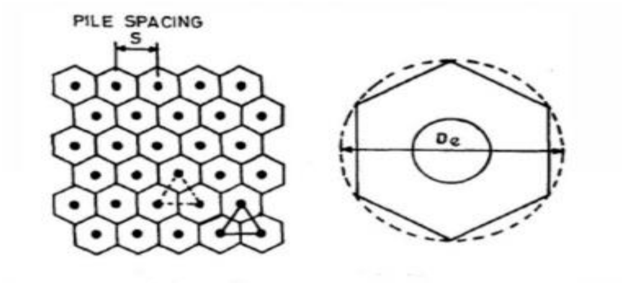

Fig. 2. Triangular pattern of stone column

3.5 Load carrying capacity of stone column

The failure of the stone column [9] is primarily by bulging into the surrounding soil. Hence, the load carrying capacity of the treated ground can be obtained by summing up the contribution of each of the following components, for wide spread loads (in Embankments):

a) Capacity of the stone column resulting from the resistance offered by the surrounding soil against its lateral deformation (bulging) under axial load.

b) Capacity of the stone column resulting from increase in resistance offered by the surrounding soil due to surcharge over it.

c) Bearing support provided by the intervening soil between the columns.

The ultimate load carrying capacity of stone column is verified by initial load test.

3.6 Settlement analysis

Settlement for the ground treated by the stone column should be computed by the Reduced stress method as per Appendix B to IS 15284 (Part 1):2003[9]. However, initial load tests (single and three-column group) are performed to evaluate the load settlement behaviour of the stone column system.

3.7 Layout of the Stone Column

As per the contract specifications, the ground improvement is to be done below the proposed bank and up to 3m on either side, so that each column below the Embankment is confined and has bearing capacity as per design. However, in case of existing track bank, the stone column is to be restricted to the toe of the existing

bank.
The typical section and layout of the stone column is shown in Figure 3.

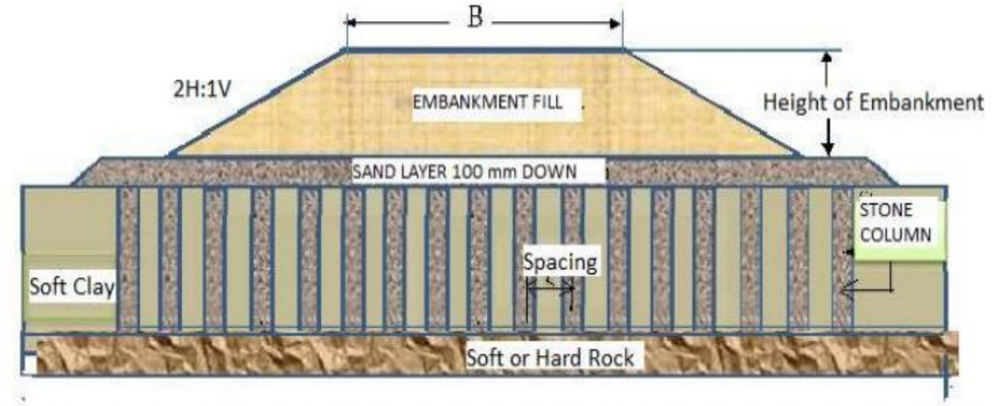

Fig. 3. Typical section of layout of stone column

3.8 Stage-loading to achieve required residual settlements

The allowable residual settlement during the operational time is 100mm. To achieve the 100mm settlement, a suitable stage-loading requirement with time period is assessed using the consolidation theory [10].

The basis of arriving at the preloading and time period is explained below:
Consider the settlement due to DL+LL = Sset (in mm)
Required settlement before the start of operations = Sreq = Sset – 100 (in mm)
Required preloading to achieve above settlement Seq = iterations done to achieve preloading to limit the consolidation time between 40 to 75 days.

The consolidation theory is used to estimate the time rate settlement to achieve required preloading with the limited time period. However, this stage loading and time period can be increased or decreased during the execution based on the available time and space as well as the actual observed settlements at site.

3.9 Summary of design of stone columns

Stone column capacity

The designed stone column diameter and spacing along with load on columns and capacity of stone columns[9] are provided in Table 3.

Based on the criteria the stone columns were designed as per IS 15284. The Salient features of the improvement technique are –

Dia. of Stone Columns (D)	900 mm
Depth of Stone Columns	8–14 m
Grid Pattern	Triangular
Spacing of stone Columns (S)	2.40 m
Design Capacity of Column	290kN

The safe load carrying capacity of a single stone column and its tributary area was estimated as 320kN. The ultimate bearing capacity of improved ground under effective area of each column works out to be 68kN/m^2 as against the ultimate bearing capacity of 29kN/m^2 of founding strata without ground improvement.

Table 3. Summary of Ground Improvement

Chainage	D (m)	S (m)	Depth of soft clay below NGL (m)*	Design Height of Embankment (m)	Maximum intensity from Embankment (kPa)	Required load carrying capacity of Ground (kPa)
CH 2+800 TO CH 4+000	0.9	2.4	8.5 to 14	2.500	56.4	64

* The stone column depth varies based on the hard stratum/rock availability. The soil profile and typical cross section of this stretch are shown in Figure 1 & 3 respectively.

Settlement Summary

Settlements are estimated for not treated ground and treated ground as per IS: 15824 (Part1) and are summarized in Table -4.

Total settlement of untreated ground with 6 and 12.5m thick marine clay strata was estimated as 1227 and 1592mm respectively at the centre of the embankment and that of ground reinforced with stone columns was 859 and 1114mm respectively. Thus, with stone column reinforcement, there is a reduction of 30% settlement.

Table 4. Summary of Settlement Analysis

Chainage	D (m)	S (m)	Clay layer thickness (m)	Settlement Before treatment (mm)	Settlement after treatment (mm)
CH 2+800 TO CH 4+000	0.9	2.4	12	1903	1376

Required surcharge load is estimated with the time required to maintain the surcharge loading to obtain the residual settlement of 100mm as per contractual requirements. The details are given in Table 5.

Table 5. Summary of Preloading and Time required to arrive at the residual settlement

Chainage	D (m)	S (m)	Stage 1 - stage platform loading (SQ1*) (m)	Time period for Stage 1 (days)	Stage 2 - Loading- 0.6m (Sand/10mm down stone aggregate)+SQ1 fill+ Subgrade (m)	Time Period for Stage 2 Loading to attain 100mm residual settlement (days)
CH 2+800 TO CH 4+000	0.9	2.4	0.6	38	0.6 + 1.4 = 2.0	60

However, for settlement monitoring[10], instruments are installed to monitor the actual settlements at every 250m interval. Using the Asaoka method[1], the final settlements are estimated based on the observed field settlements. Settlement monitoring instruments[10] are installed immediately after stone column installation and continuous monitoring records are maintained. Final embankment levels are arrived based on the Asaoka settlement graph plot (Fig.4) the final assessment of settlement and the design time are reverified at site. The top subgrade layer is to be removed to accommodate 0.6m of blanketing.

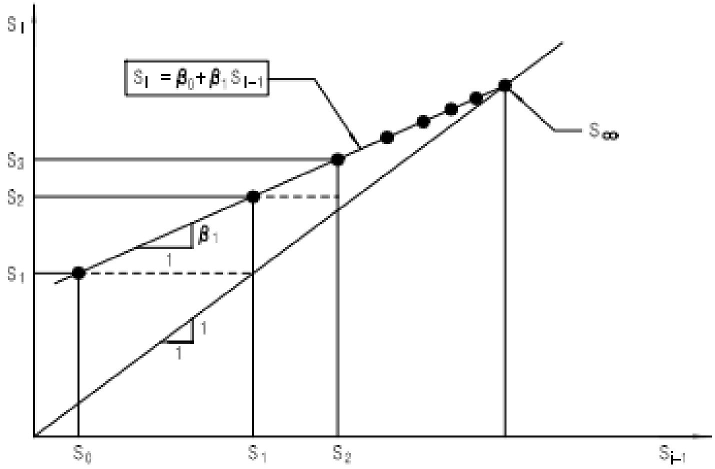

Fig. 4. Asaoka's Graphical Method of Settlement prediction

3.10 Stability analysis

Stability analysis of embankment with and without stone columns was carried out using slope stability software 'SLOPE/W' of Geoslope International Ltd. Factor of safety without stone column reinforcement was 0.838. For short-term stability, the reinforced ground was modelled as 900mm diameter vertical columns of stones with density of 22 kN/m3, angle of internal friction 40deg and at centre-to-centre spacing of 2.4m confined by soft marine clay with un-drained cohesion of 22.5kPa. The factor of safety was found to be 1.916 (Fig. 5). Considering the embankment load application to enforce settlement and quick drainage path provided by stone columns for consolidation, long-term safety factor would definitely be more than the value estimated as above.

Table 6. Slope stability analysis summary

DFCC Chainage	Embankment Fill Height (m)	Proposed Slope	Factor of Safety Static Case	Factor of Safety Seismic Case
2+800 to 4+000 (No treatment)	2.4	2H:1V	0.838	0.562
2+800 to 4+000 (with treatment)	2.4	2H:1V	1.916	1.267

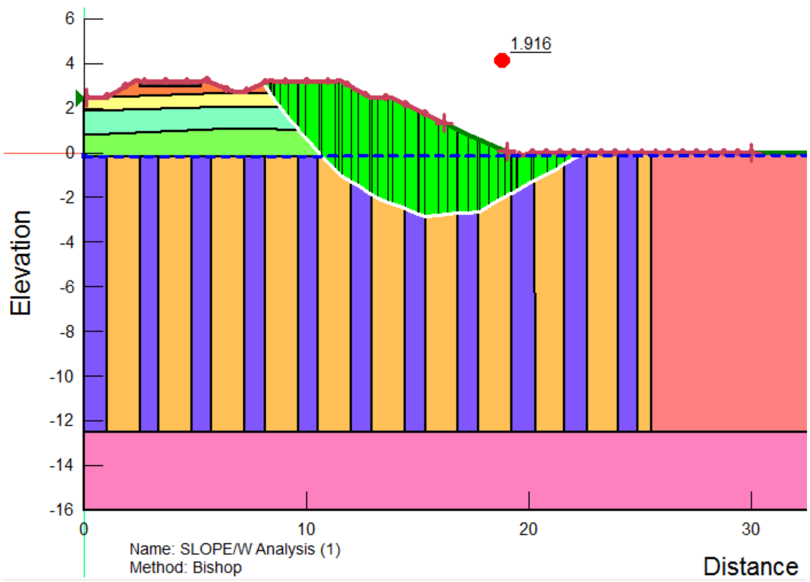

Fig. 5. Stability Analysis of Embankment with Stone Column Reinforcement

4 Construction of Non-Vibro Stone Column

Stone Columns[9] were installed by Non-Vibro Displacement method using Casagrande B 175/200 type Hydraulic Rig. The columns were installed using Bottom feed Dry process. The method for construction[2&3] of the stone columns is illustrated in Fig. 6 to Fig. 11.

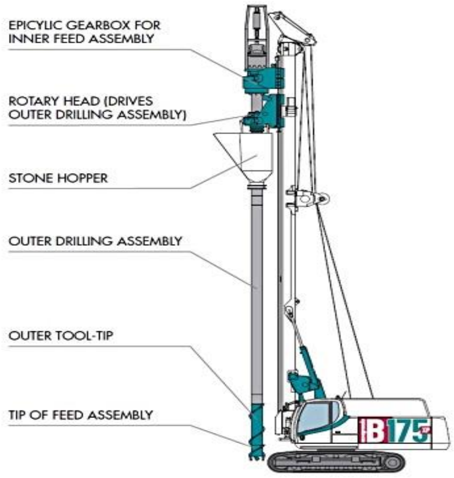

Fig. 6. Assembly for Non-Vibration Stone Column

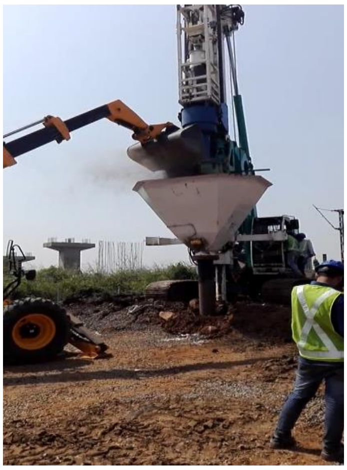

Fig. 7. Loading of Stone into the Hopper

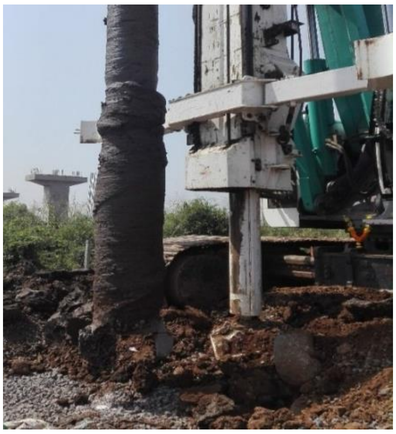

Fig. 8. Rotating Screw Assembly

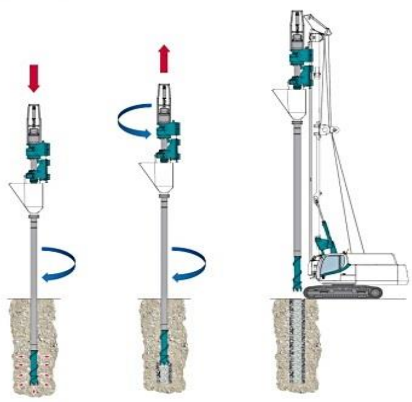

Fig. 9. Process of Installation of Stone Column

(Courtesy: Jaron Lyell McMillan)

Fig. 10. Torque applied during initial boring of column

Fig. 11. Torque applied during column compaction

5 Load Test

The initial load test on single stone column as well as three-column group was conducted in terms of clause 13 of IS 15284. As per this clause, the load test should be considered acceptable if it meets the following settlement criteria[9]:

i) 10 to 12 mm settlement at design load for a single column test, and
ii) 25 to 30 mm settlement at the design load for a three-column group test.

The initial load test values for single column test was obtained as 3mm, while for three column group as 7mm, which is much below the stipulated values, as given above.The routine load tests is performed at a frequency of 1 test per 625 m2. The results of the routine load tests showed almost similar values of settlements.

5.1 Single column load test

For Single column load test[9], centre column in a group of seven columns as shown in Fig. 12 was selected as test column and the test setup is as shown in Fig. 13. The design load was considered as the safe load on column (excluding the safe load which will be taken by soil) i.e. 320kN.

Hence, the test load was 320 * 1.50 = 480kN.

The total settlement of 6.145 mm and net settlement of 4.10 mm was observed. The settlement at design load of 320kN was 3.25 mm. The load settlement graphs are shown in Fig. 14 and Fig. 15.

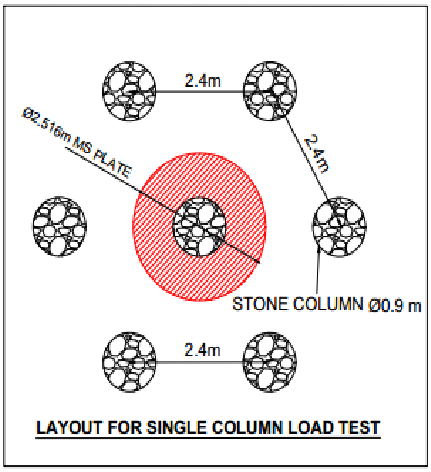

Fig. 12. Layout for Single Column Load Test

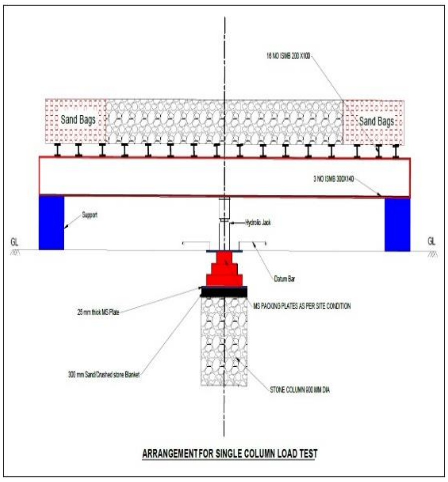

Fig. 13. Test Arrangement for Single-Column Load Test

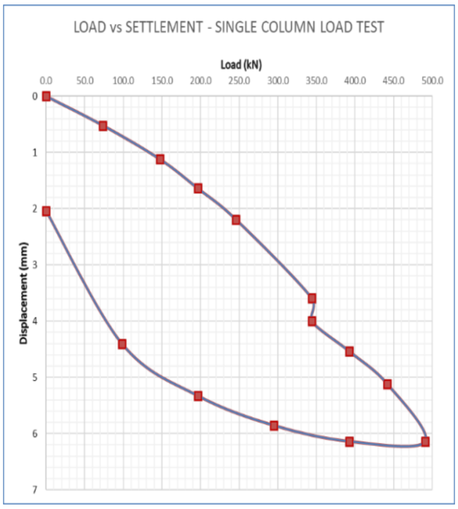

Fig. 14. Load Settlement Curve for Single Column Load Test

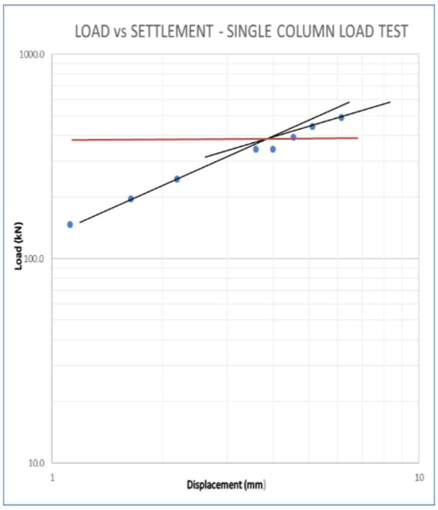

Fig. 15. Log-log Curve for Single Column Load Test

Fig. 16. Test Setup

5.2 Three column load test

For Three Column load test[9], three columns at the centre in a group of fifteen columns as shown in Fig. 17 were selected as test columns and the test setup is shown in Fig. 18. The design load was considered as the safe load on column (excluding the safe load which will be taken by soil) i.e. 960kN.

Hence, the test load was = 960 * 1.50 = 1440kN.

The total settlement of 13.062 mm and net settlement of 7.12mm was observed. The settlement at design load of 960kN was 5.96 mm. The load settlement graph is shown in Fig. 19 and Fig. 20.

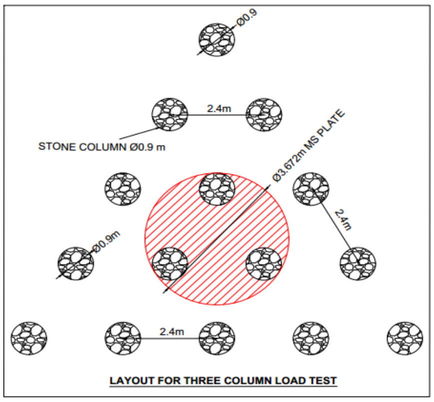

Fig. 17. Layout for Three Column Load Test

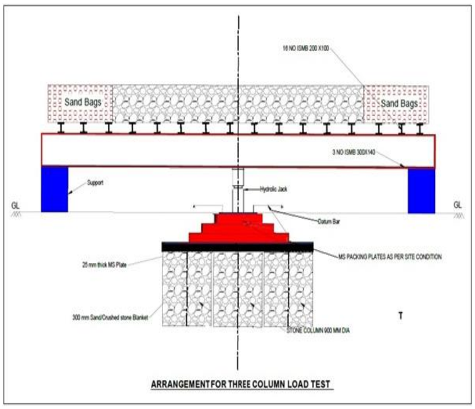

Fig. 18. Test Arrangement for Three-Column Load Test

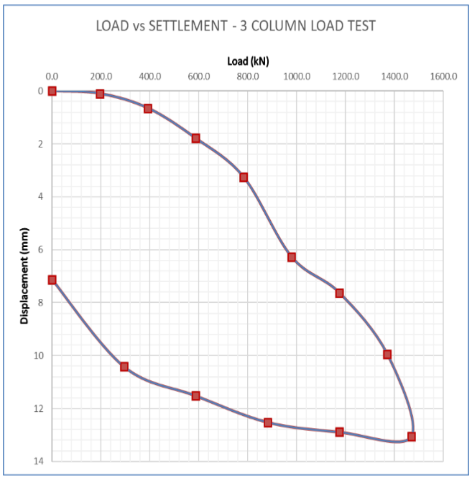

Fig. 19. Load Settlement Curve for Three Column Load Test

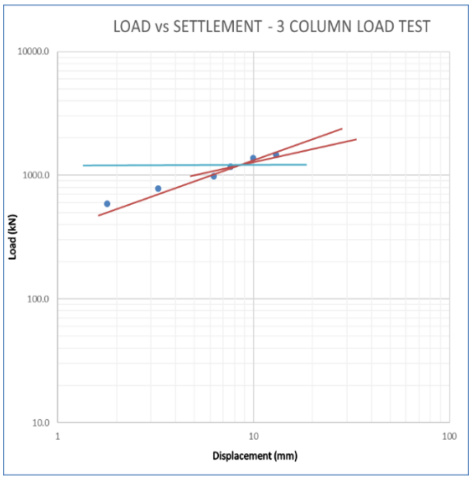

Fig. 20. Log-log Curve for Three Column Load Test

If certain parameters of stone columns of single column load test and three column load test are compared (Fig.21), The ultimate load works out to be about 480kN for the single column test and the corresponding settlement is about 6mm and for three column test, the ultimate load is about 1440kN and the corresponding settlement is about 13mm. Thus, in-group case ultimate load per column is 1440kN which is higher (about 33%) than the single column case. Thus, an isolated single column compared to a group of columns has a slightly lesser ultimate load capacity per column in a group. This may be because as surrounding columns are added to form a group, the surrounding columns and the rein-forced ground confine the interior columns. From group test results, the ultimate bearing capacity of improved ground works out to be 70kN/m^2.

Thus, it appears that the performance of the stone columns in group is better than single column test although settlements are slightly higher. The larger bearing area in group test which simulates the site condition, together with the additional support of the stone column results in less bulging and a greater ultimate load capacity. The observed settlements are acceptable for the embankment; hence, the required factor of safety for the improved ground has been achieved.

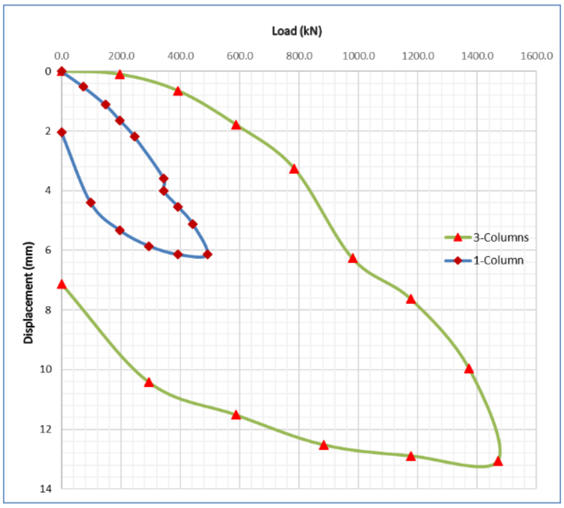

Fig. 21. Load Settlement Curves Comparison

6 Conclusions

The non-vibro stone column method is being used in India for the first time under DFCCIL project. Use of the latest technology of non-vibration method of driving stone column not only avoids any danger of settlement to the existing tracks or nearby structure and utilities but also leads to higher bearing capacities and lesser settlements. The method gives better quality of the stone column and higher displacement of the surrounding soil.

Behaviour of single and group of stone columns have been presented. Criteria adopted for arriving at required factor of safety based on the settlement observed has been presented. The observation of actual settlement versus time such as in Asaoka method[1] can help modifying the settlement calculations for the method and bring it closer to the actual observed values. This can thus reduce preloading[3] time and can lead to faster construction after soil improvement. Although the spacing of stone columns[9] and hence the area replacement ratio were high in this case the slope stability analysis[4] carried out with stone column reinforced ground model, gave confidence to go ahead with the improvement pattern.

Single and group of stone columns have performed satisfactorily during the testing and desired factor of safety has been achieved, however, without the group load testing certain decisions regarding stability would not have been possible. Performance of stone columns in-group test have been found to better than single column test. As load test data on stone columns is scanty in literature, it is felt that the results of footing load tests carried out on single and group of stone columns, presented in this paper would be useful to practicing engineers.

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