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Performance of Rammed Stone Column Foundations in Alluvial Soils

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Introduction

Rammed Stone Column (RSC) technique, one of the most versatile ground strengthening methods has been extensively used to support flexible structures (where relatively larger settlements can be allowed safely), resting on soft cohesive soils and weak to marginal soils of cohesionless nature extending upto depths of about 15 m (IS 15284 Part I: 2003). Further, small diameter gravel piles have also been used for strengthening of ground to support building foundations in loose/soft soil deposits of shallow depths (Singh et al., 1988). The beneficial effects of installation of RSCs in weak or loose soils are manifested in the form of increased load carrying capacity, significant reduction in settlements, accelerated consolidation, minimization of liquefaction risk and thus effective change in the dynamic response (Saha and Das, 1999).

The installation of stone columns generally involves creation of a borehole in the ground, subsequently filling it with a granular material and then compacting it by a suitable means (IS 15284 Part I: 2003). For accomplishing the borehole, use of conventional boring equipments are becoming popular owing to their simplicity in operation. Normal method of boring by direct mud circulation (DMC) has been preferred in the recent times particularly in sandy and silty soils in view of their good drainage characteristics.

The performance of rammed stone column foundation is assessed based on two criteria: (i) load carrying capacity should be sufficient enough to take

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care of the external loads and (ii) the settlement of the composite ground strengthened with RSCs should be within the permissible limits. These aspects are further governed by various factors, viz., type of soil to be strengthened, area and depth of treatment desired, construction methodology adopted, and on the design parameters like diameter of stone column, spacing between the columns, pattern of installation, tributary area of soil surrounding the stone column, etc. Though many approaches discuss about bearing capacity, settlements and construction methodology of stone columns, still uncertainty exists in the design and construction aspects (Prakash et al., 2000) for practicing engineers and more or less the problem, as a whole has to be dealt site-specific. Hence, the most commonly followed in-situ control test in India is, a load test on a rigid plate covering single/group of RSCs and their tributary area (Bhandari and Nayak, 1984; Sundaram and Gupta, 1994; Madhav et al., 1999; Prakash et al., 2002).

The paper demonstrates the application and performance of rammed stone columns for strengthening wide variety of alluvial soils ranging from loose to medium dense sands / silty sands and clayey silt / silty clay soils with and without fill over them with reference to authors experience with five field cases. Numerous field data has been presented and the extent of ground improvement and settlement reduction achieved in each case have been discussed on the basis of analysis of results of load tests and penetration tests prior to and after construction of RSCs. A procedure to extrapolate the results of plate load tests to predict the behaviour of actual RSC-treated ground in the five cases using the settlement factors of Madhav et al. (1999) is also briefly outlined.

Details of Field Cases

Case I

The site consists of silty sand / poorly graded fine sand to depths of about 8 m followed by stiff to very stiff clayey silt strata upto depths of about 14-15 m. The ground water table was at a shallow depth of 3 m. Typical bore hole profile along with SPT-N values is given in Fig.1a. The average in-situ shear strength of the strata interpreted from the field and laboratory investigations is about 23 kPa. A mounded LPG storage facility (3 bullets, each of 7.1 m diameter and 88.02 m length) with a design load of 230 kPa and an allowable settlement of 60 mm was to be set up. Considering these sub-soil strata conditions, design loading intensities and in order to keep the settlements within the permissible limits, rammed stone columns (RSCs) of 500 mm diameter and 12 m depth below existing ground level at a spacing of 1.65 m c/c (3.3 times the diameter of the column) have been provided in a triangular pattern as a strengthening measure.

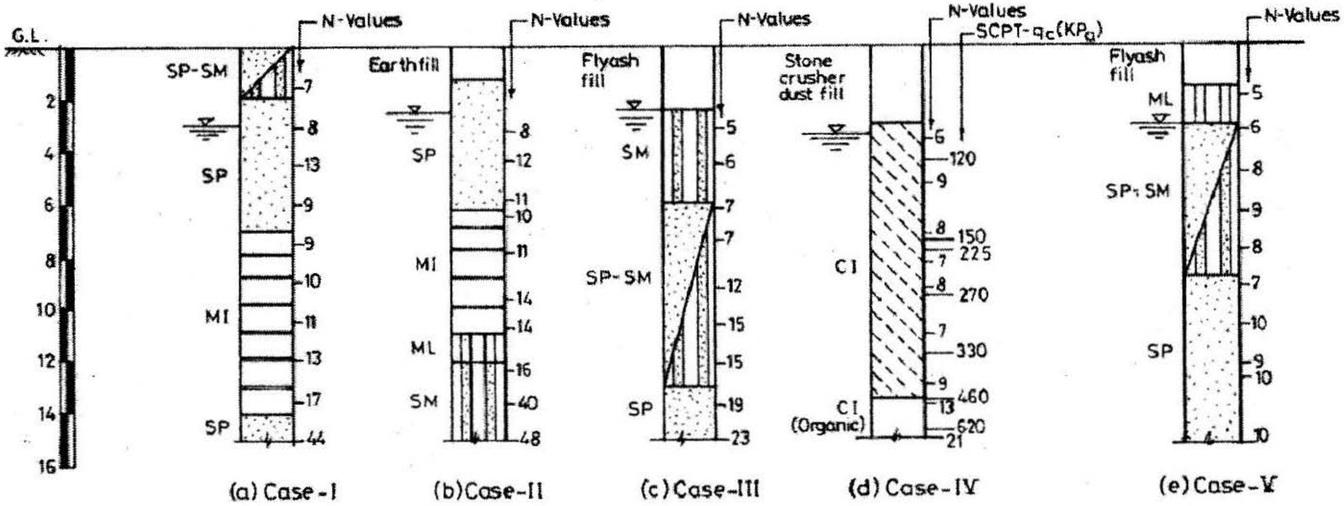


FIGURE 1 : Typical Bore Hole Profiles at Site Locations of Field Cases

Case II

At this site also, the structure similar to that of Case-I was to be set up with the design load of 230 kPa and allowable settlement of 60 mm. However, the terrain at this location was highly undulated, having a level difference of 0.5 m to 2.5 m with the sub-soil strata consisting of poorly graded fine sand to depths of about 6 m followed by medium stiff clayey silt upto about 12 m and further by stiff to very stiff clayey silt/silty sand strata. Typical bore hole profile along with SPT-N values is given in Fig.1b. The average in-situ shear strength of the strata interpreted from the field and laboratory investigations is about 21 kPa. The undulations were initially made up with the earth filling and then rammed stone columns (RSCs) of 500 mm diameter and 12 m depth below the top of earth fill at a spacing of 1.4 m c/c (2.8 times the diameter of column) and in a triangular pattern have been provided as a strengthening measure to keep the settlements within the permissible limits.

Case III

This site location was low-lying by about 2.5 m and remained inundated during monsoon every year. A mounded LPG storage facility (3 bullets, each of 7.0 m diameter and 79.65 m length) with a design load of 210 kPa and allowable settlement of 60 mm was to be set up on the sub-soil consisting of loose silty sand / poorly graded fine sand upto about 12.0 m depth followed by medium dense sandy strata. Typical bore hole profile along with SPT-N values is given in Fig.1c. The average in-situ shear strength of the strata interpreted from the field and laboratory investigations is about 17 kPa. Initially, the low-lying ground level has been raised by 2.5 m using fly ash fill and then rammed stone columns (RSCs) of 500 mm diameter and 12 m depth below the top of fly ash fill (i.e. about 9.5 m below the natural ground level) at a spacing of 1.355 m c/c (2.71 times the diameter of column) and in a triangular pattern have been provided as a strengthening measure.

Case IV

At this site, the sub-soil consists of low to medium compressible clayey silt / silty clay upto about 12 m followed by medium to stiff organic clayey strata. A mounded LPG storage facility (4 bullets, each of 4.0 m diameter and 62 m length) with a design load of 200 kPa and allowable settlement of 60 mm was to be set up. The ground water table was at a depth of about 3 m but likely to raise to ground surface and above during rainy season. Typical borehole profile along with SPT-N values and SCPT-q_c values is given in Fig.1d. The average in-situ shear strength of the strata interpreted from the field and laboratory investigations is about 20 kPa. In view of the project requirements at site, initially, the level of the ground surface had been raised by about 3.0 m using locally available stone crusher dust fill material (particle size equivalent to fine to medium sand with silt content less than 5%) and then rammed stone columns (RSCs) of 600 mm diameter and 14.25 m depth below the top of stone crusher dust fill (i.e. about 11.25 m below NGL) at a spacing of 1.59 m c/c (2.65 times the diameter of column) and in a triangular pattern have been provided as a strengthening measure.

Case V

Three water tanks of 22 m diameter and 10 m height with a design loading intensity of 120 kPa and maximum allowable settlement of 100 mm at the center of the tank were to be founded in this site with the sub-soil consisting of predominantly silty sand / poorly graded fine sand extending upto greater depths. SPT- N values are of the order of 5-10 even to depths of 15 m. Ground water table existed at about 3 m depth at the time of exploration, however, the site remains mostly inundated during rainy season. Accordingly, the site had been raised by fly ash filling. Typical bore hole profile along with SPT-N values are given in Fig.1e. The average in-situ shear strength of the strata interpreted from the field and laboratory investigations is about 19 kPa. In view of the above soil strata conditions and design loading intensities, rammed stone columns (RSCs) of 400 mm diameter and 12 m depth below existing ground level at a spacing of 1.6 m c/c (4 times the diameter of the column) have been provided in a triangular pattern as a strengthening measure.

The complete details of these schemes have been discussed by Prakash et al. (1998, 2002). The design and construction procedures followed for the RSCs, field tests carried out and their analysis and discussion are presented in the following paragraphs.

Design and Construction of RSCs

For the design of rammed stone columns, the safe capacity of a single RSC has been estimated in general in accordance with the guidelines, given in IS 15284 (Part I): 2003 considering the contributions from (i) bulging action, (ii) surcharge effects and (iii) intervening soil and adopting suitable factors of safety for each component. Further, the number of columns and the spacing between the columns have been decided based on the design loading intensity, plan area of the structure and the allowable settlements (total / differential) in each case. The settlement of the RSC has been estimated considering the strain compatibility at the top of column, by assuming uniform stress and volume compressibility characteristics throughout the length of column.

For construction of RSCs, the boring has been done following normal direct mud circulation (DMC) method with a 3 m casing in the top portion. In Cases I, II, III and V, where the strata is predominantly sandy / silty sand type with good drainage characteristics, the boreholes have been stabilized with continuous supply of bentonite slurry. In Case IV, in view of clayey silt / medium stiff clayey strata conditions, boreholes could be accomplished without using bentonite at all. Pumping out bentonite mud, replacement with clean water etc. has not been found necessary in any of these sites. In general, coarse aggregate of about 63 mm and down size of equivalent height of about 500-750 mm and coarse sand of equivalent height of about 250 mm have been placed in each layer. For compacting each layer, minimum, 40 blows of a rammer of specified weight of about 10.0 kN with a specified height of fall of about 1.0 m have been fixed subjected to a condition that a set of 10 mm or less could be achieved in the last 10 blows. The compression of charge for each 10 blows and the consumption of materials have been recorded for each layer. The process has been repeated upto the top of the borehole. The construction procedure adopted is shown in Fig.2.

Field Tests

In order to verify the design capacities and to evaluate the performance of rammed stone columns, field tests have been conducted before as well as after construction of RSCs in each case. The field tests have been conducted in two stages, first during initial field trials and then on the working RSCs.

During the initial field trials, load tests on three groups of three RSCs at spacing varying between 2.5D - 4.0D (where D is the diameter of initial

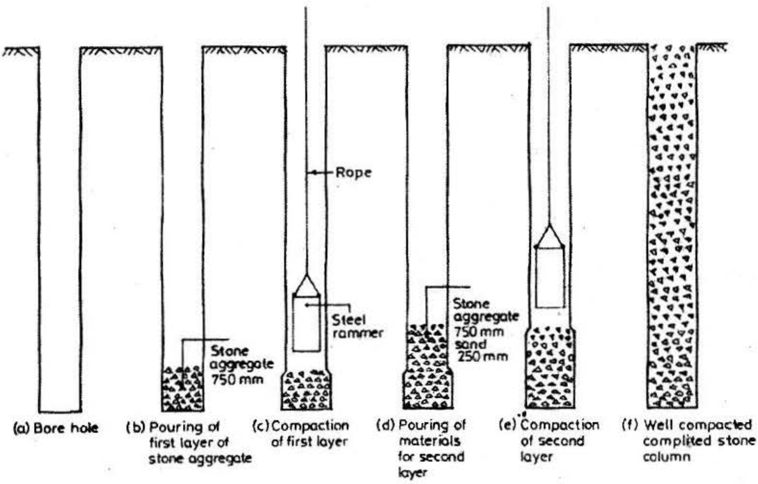


FIGURE 2 : Construction Procedure of Rammed Stone Columns

bore hole) as well as a few dynamic cone penetration tests have been conducted to assess the extent of improvement and to check the uniformity of the same along the depth of the strata. Based on these trials, the spacings and construction controls for the working RSCs have been decided in each case. After construction of working RSCs in each case, a few load tests on single RSCs as well as group of three RSCs have been conducted.

Dynamic cone penetration tests (DCPT) have been conducted using 50 mm cone and in accordance with guidelines given in IS 4968 (Part I): 1976 at all the three group locations during initial field trials in each case. One DCPT before the construction of RSCs at each group location as well as four DCPTs (one at center of the group and other three at the center of the three respective sides joining the stone columns) after construction of group of three RSCs as shown in Fig.3 have been conducted.

For conducting the load tests on RSCs during initial field trials as well as on working RSCs, area at each single RSC / group of RSCs has been excavated and a well compacted 63 mm down size coarse aggregate of about 200 mm thickness has been laid as sub-base. The size of the sub-base has been about 1.5 m × 1.5 m for single RSCs and 3.5 m × 3.5 m for group of RSCs. The load tests on single stone column has been carried out by placing a plate of 1.0 m × 1.0 m × 25 mm size concentric with the column's axis (Fig.4). The load tests on group of three stone columns has been carried out using a plate of 1.5 m × 1.5 m × 40 mm size placed in such a way that the C.G. of the plate and C.G. of the group coincide with each other (Fig.5). In view of the non-availability of the circular plates of above sizes, square plates of equivalent area have been used. Prior to construction of RSCs, load tests on plates of the same size but directly resting on sub-base have also been conducted to assess the extent of improvement. The tests have been conducted upto a loading intensity of 3 times the design loading intensity during initial trials and 2 times the design loading intensity for working RSCs. The settlement of the plate has been measured by 4 dial gauges placed at the four comers of the plate. The testing procedure, i.e., load steps and the criterion for rate of reduction in settlement etc. have been in accordance with guidelines given in IS 1888: 1982 during both initial trials as well as for working RSCs.

Results and Discussion

Initial field trials

The DCPT results before and after construction of groups of RSCs have also indicated a significant improvement with the use of RSCs at all the three group locations in all the five cases. The average dynamic cone penetration resistance improvement ratio (DCPRIR) as defined below while

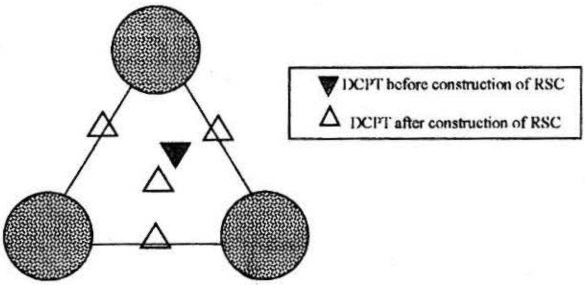


FIGURE 3 : DCPT Locations Before and After Construction of RSCs

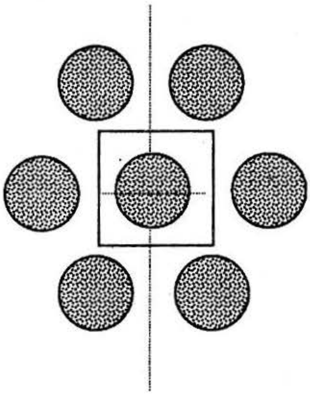


FIGURE 4 : Orientation of Plate for Load Test on Single RSC

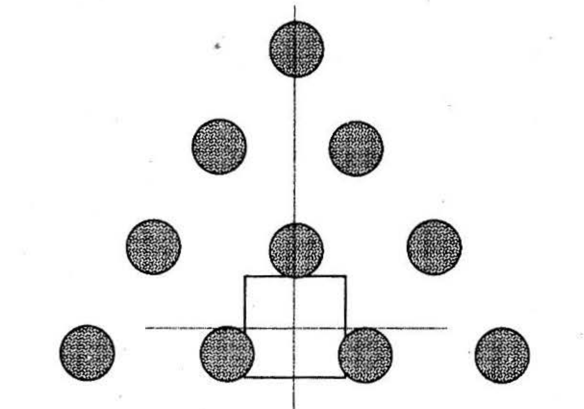


FIGURE 5 : Orientation of Plate for Load Test on Group of RSCs

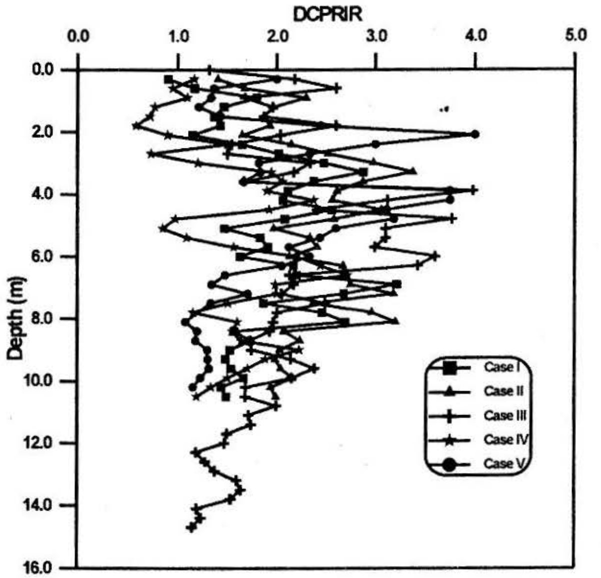


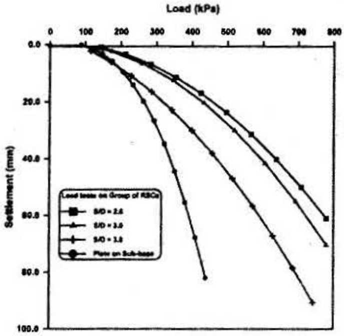
FIGURE 6 : Dynamic Cone Penetration Resistance Improvement Ratio along the Depth

plotted against depth (Fig.6) reveals that there is an improvement in DCPT resistance of about one to four times, with an average of at least two times through out the depth in all the cases.

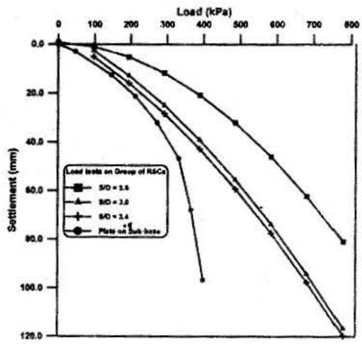
$$\text{DCPRIR} = \frac{\text{DCPT resistance after construction of RSCs}}{\text{DCPT resistance before construction of RSCs}} \quad (1)$$

The marginal decrease in resistance (DCPRIR < 1) in Case IV within the top about 3 m, i.e., fill depth may be due to reduction in strength of compacted stone crusher dust fill on account of moisture migration into the fill during the installation of RSCs. However, an increased resistance could be seen below this depth.

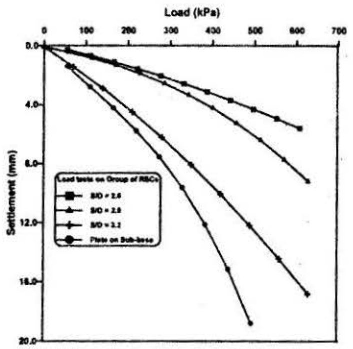
Further, Figs.7a to 7e show the load-settlement response of group of RSCs at various spacings along with those of comparable plates directly resting on sub-base for the five field cases respectively during initial field trials. The trends of the curves are almost same in all the five cases indicating that there is an obvious improvement in the behaviour with the use of RSCs at all the spacings. However, more improvement could be seen at closer spacings (S/D) and the extent of improvement has reduced with the increase in spacing. The extent of improvement with respect to spacings has been



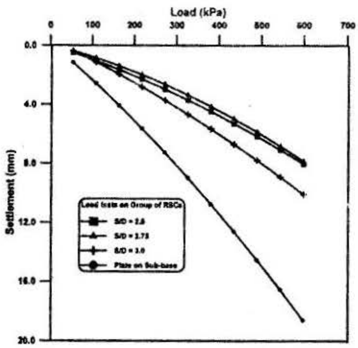
(a) – Case I



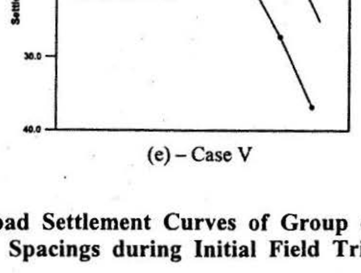
(b) – Case II



(c) – Case III



(d) – Case IV



(e) – Case V

FIGURE 7 : Load Settlement Curves of Group of RSCs at Various Spacings during Initial Field Trials

different from case to case in view of the difference in sub-soil strata and site conditions.

Thus from the above DCPT and load test results, it is understood that even with the construction of a few set of RSCs for initial trials, there has been an immediate improvement in the ground characteristics.

Accordingly, considering the improvement in the DCPT resistance along the depth as well as the settlement reduction observed in load tests with respect to various spacings tried, and also from the point of view of the optimization of number of RSCs in each case, the spacings for the working RSCs have been decided for each case as given in Table 1.

Load-settlement response of Working RSCs

Figures 8a to 8e show the load-settlement response curves of single working RSCs along with those of comparable plates tested before the construction of RSCs for the five cases respectively. Although in each case, numbers of load tests have been conducted as given in Table 1, the average behaviour is represented in these figures. From these curves, it can be seen that the load–settlement curves have not shown any yield even upto the maximum loading intensities of 400-500 kPa whereas the comparable plate without RSCs has settled greatly under the same loading intensities.

Similar kind of improvement has been observed from the load-settlement response of group of working RSCs as seen from Figs.9a to 9e for the five cases respectively. Thus, it is clear that there is a significant improvement in the behaviour of the ground and the settlements reduced considerably after installation of RSCs in all the five cases. The reasons could be mainly due to the compaction of the surrounding ground and to quality controls over size and gradation of the coarse aggregate, ramming energy, set criterion etc. strictly followed during the execution of RSCs.

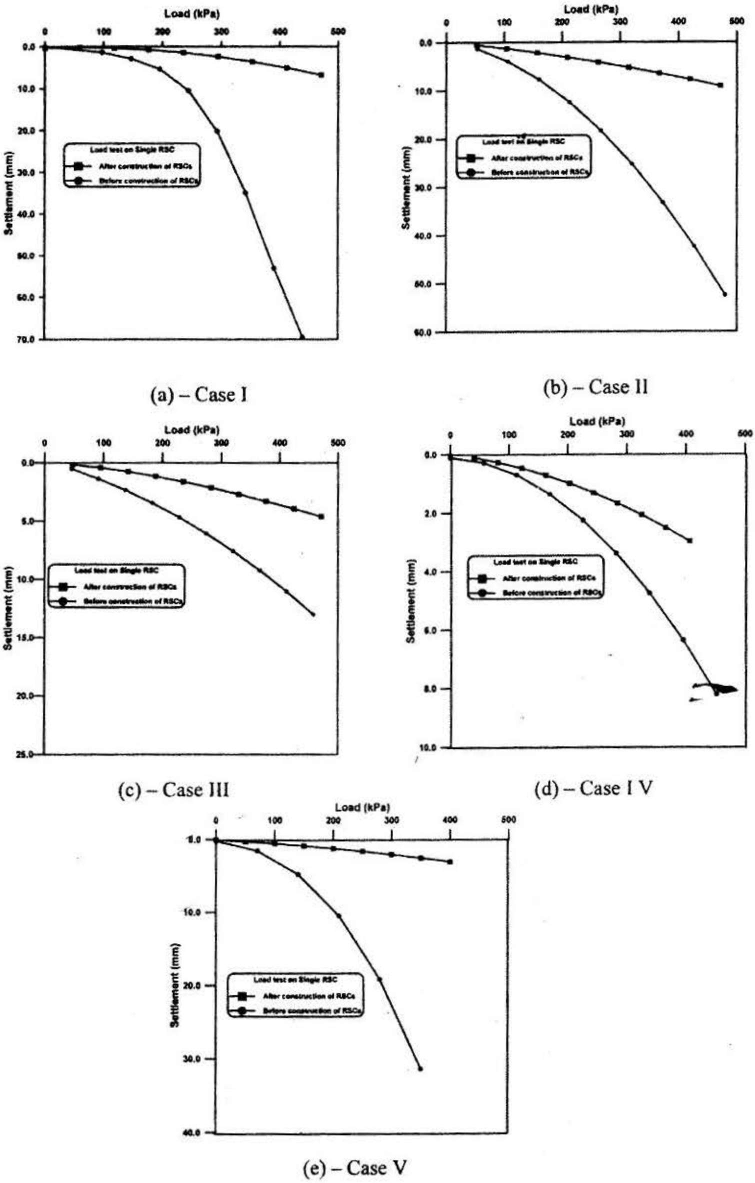
The design loading intensities (DLI), settlements corresponding to design loading intensity as well as at 2 times the design load (2 * DLI – which can be almost taken as the ultimate load or the maximum load upto which the tests are in general conducted), along with the settlement reduction ratio based on these plate load test results β_{plate} as defined below etc. in each case are summarized in Table 1.

$$\beta_{\text{plate}} = \frac{\text{Settlement of the plate supported by RSCs}}{\text{Settlement of the plate on ground without RSCs}} \tag{2}$$

From the table, it is noted that the β_{plate} values (Lesser value of β_{plate}

TABLE 1 : Details of Load Tests and the Settlements

Case	Test Description	Plate size (m x m)	(S/D) for Working RSCs	No. of Tests	Design Loading Intensity - DLI (kPa)	Settlement (mm) corresponding to		Settlement reduction ratio $[\beta]_{plate}$	
						DLI	2*DLI	DLI	2*DLI
I	Single RSC	1.0 x 1.0	3.30	3	230	1.79	6.07	0.21	0.07
	Plate on Sub-base	1.0 x 1.0	-	1		8.57	83.6	-	-
	Group of RSCs	1.5 x 1.5	3.30	5		5.45	19.1	0.37	0.21
	Plate on Sub-base	1.5 x 1.5	-	1		14.5	94.5	-	-
II	Single RSC	1.0 x 1.0	2.80	4	230	4.00	21.0	0.28	0.23
	Plate on Sub-base	1.0 x 1.0	-	1		14.0	89.0	-	-
	Group of RSCs	1.5 x 1.5	2.80	4		3.00	10.0	0.14	0.10
	Plate on Sub-base	1.5 x 1.5	-	1		22.0	96.8	-	-
III	Single RSC	1.0 x 1.0	2.71	5	210	1.33	3.50	0.31	0.30
	Plate on Sub-base	1.0 x 1.0	-	1		4.33	11.7	-	-
	Group of RSCs	1.5 x 1.5	2.71	4		1.80	4.5	0.33	0.32
	Plate on Sub-base	1.5 x 1.5	-	1		5.40	14.2	-	-
IV	Single RSC	1.0 x 1.0	2.65	2	200	0.83	2.76	0.46	0.44
	Plate on Sub-base	1.0 x 1.0	-	1		1.81	6.29	-	-
	Group of RSCs	1.5 x 1.5	2.65	3		2.00	4.10	0.41	0.40
	Plate on Sub-base	1.5 x 1.5	-	1		4.83	10.2	-	-
V	Single RSC	1.0 x 1.0	4.00	3	120	0.88	2.01	0.20	0.15
	Plate on Sub-base	1.0 x 1.0	-	1		4.44	13.33	-	-
	Group of RSCs	1.5 x 1.5	4.00	1		0.45	0.90	0.08	0.06
	Plate on Sub-base	1.5 x 1.5	-	1		5.45	15.90	-	-



(a) – Case I

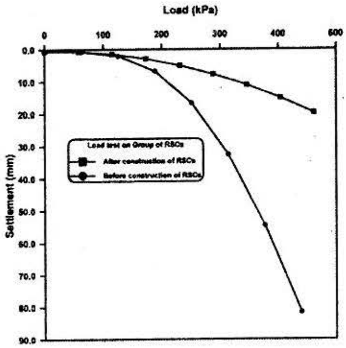
(b) – Case II

(c) – Case III

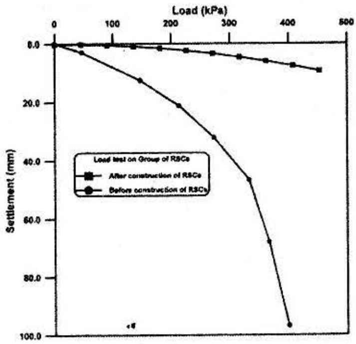
(d) – Case I V

(e) – Case V

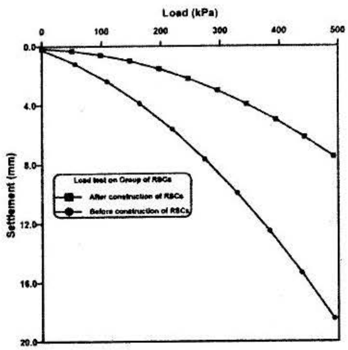
FIGURE 8 : Load Settlement Curves of Single Working RSCs



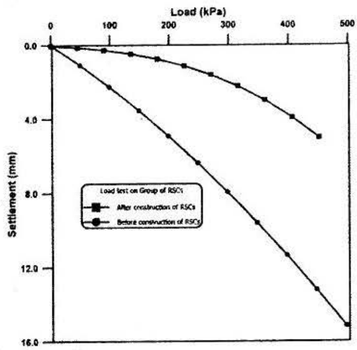
(a) – Case I



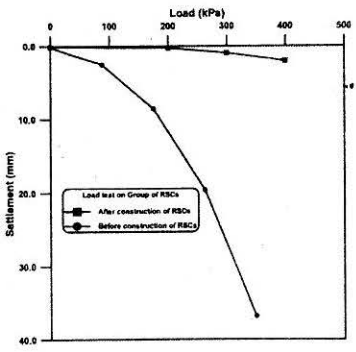
(b) – Case II



(c) – Case III



(d) – Case I V



(e) – Case V

FIGURE 9 : Load Settlement Curves of Group of Working RSCs

indicates greater improvement and vice-versa) at DLI are in the range of 0.21 to 0.37 (63 to 79% improvement) for Case I; 0.14 to 0.28 (72 to 86% improvement) for Case II; 0.31 to 0.33 (67 to 69% improvement) for Case III; 0.41 to 0.46 (54 to 59% improvement) for Case IV and 0.08 to 0.20 (80 to 92% improvement) for Case V. Slightly more values of β_{plate}, i.e., lesser improvement observed in Case IV is mainly due to sub-soil strata being predominantly clayey type and the presence of stone crusher dust fill of huge thickness of about 3.0 m at the top of RSCs and thus the presence of fine particles, low permeability, compaction properties etc. as well as the drainage and saturation effects of the fill material during the installation of RSCs also slightly affect the behaviour.

Though it is not fair to make extrapolation of the above β_{plate} values to assess the settlement reduction in actual ground treated with RSCs, it can be indirectly inferred with certain degree of error that there is more than 50% reduction in settlements in all the cases covering wide variety of alluvial soils with and without fill in the top layers.

Further, from the table, it can also be noted that in Case I, the settlement corresponding to DLI of 230 kPa is only 1.79 mm for single RSC against 8.57 mm for the comparable plate indicating a settlement reduction ratio of 0.21 and at 2 times DLI, the settlement reduction ratio has reduced to 0.07, which shows that there is a further improvement at higher loading intensities. Similar improvement is noticeable for groups of RSCs also in this case I, i.e., the settlement reduction ratio of 0.37 at DLI has reduced to 0.21 at 2 * DLI. Similar reduction (considerable to marginal) in settlement reduction ratio with increase in DLI is observed in single/group of RSCs in other cases also. Thus, the settlements are likely to reduce at higher loading intensities and hence it can be inferred that the performance of the ground treated with rammed stone columns is certainly going to be much better under the actual loading conditions and use.

Settlement of ground treated with RSCs

The interpretation of the results from the plate load tests to the actual ground situation is rather complex because the load applied through a rigid plate of size that is intermediate to those of stone column and granular sub-base over it, is shared by both stone column and the in-situ soil while the actual ground is uniformly loaded all over. Further, it is also recognized by many investigators that the unit cell can very well represent the behaviour of composite ground reinforced with stone columns. Accordingly, Madhav et al. (1999) proposed design charts for settlement factors (SF) as defined below and a simple procedure to correlate the behaviour of stone column reinforced ground from the results of load test on a rigid plate.

$$SF = \frac{\text{Settlement at the centre of unit cell}}{\text{Settlement of the rigid plate}} \tag{3}$$

Considering the above, the settlement of the actual ground treated with RSCs, ρ_{tr} in the present five cases has been estimated by multiplying the average settlement values observed from load tests in each case ρ_{avg} with the settlement factors (SF) proposed by Madhav et al. (1999).

(i) For computation of ρ_{avg}, the weighted average of number of tests on single RSCs as well as group of RSCs and the respective settlements observed in each case has been considered as follows:

$$\rho_{avg} = \frac{\left[n_{single} \times \rho_{single}\right] + \left[n_{group} \times \rho_{group}\right]}{\left[n_{single} + n_{group}\right]} \tag{4}$$

where n_{single} = Number of load tests on single RSCs in each case;

ρ_{single} = Settlement of plate supported by single RSCs in each case corresponding to DLI;

n_{group} = Number of load tests on group of RSCs in each case;

ρ_{group} = Settlement of plate supported by group of RSCs in each case corresponding to DLI.

(ii) The settlement factors (SF) from Madhav et al. (1999) have been obtained considering the (a) relative size of plate and RSC, (b) relative size of unit cell and RSC, (c) relative stiffness of RSC and ambient soil and (d) relative stiffness of granular sub-base and RSC in each case.

The settlement of the actual ground treated with RSCs assessed using the above procedure has been 7.3 mm, 6.0 mm, 6.81 mm, 6.93 mm and 2.67 mm for Cases I, II, III, IV and V respectively. These are quite nominal and well below the allowable settlement limits ensuring the successful performance of the rammed stone column foundations in all the five cases covering wide variety of alluvial sub-soil conditions presented herein this paper. This has been further confirmed from the maximum settlements values (5 to 10 mm only) noticed during hydro testing of the facilities in all the five cases.

Conclusions

The load tests data and penetration test data pertaining to five different field cases described herein revealed that the performance of rammed stone columns has been successful in alluvial soils of varied description with and without fill in the top layers. For the RSCs provided at about 2.65 to 4.0 times the diameter and in a triangular pattern, the settlements reduce more than 50% at design loads and further improvement in the performance of ground is likely at higher and actual loading intensities. The procedure outlined using plate load test results and in conjunction with settlement factors from an analysis based on unit cell can be utilized to assess the settlement of the actual ground treated with rammed stone columns with reasonable degree of accuracy.

Acknowledgement

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Notations

RSC	=	Rammed Stone Column
RSCs	=	Rammed Stone Columns
D	=	Diameter of initial borehole made for RSC
S/D	=	Spacing ratio for RSCs
DCPRIR	=	Dynamic Cone Penetration Resistance Improvement Ratio
DLI	=	Design Loading Intensity
β_{plate}	=	Settlement reduction ratio based on plate load tests
n_{single}	=	Number of load tests on single RSCs in each case
n_{group}	=	Number of load tests on group of RSCs in each case
ρ_{single}	=	Settlement of plate supported by single RSCs. in each case corresponding to DLI
ρ_{group}	=	Settlement of plate supported by group of RSCs in each case corresponding to DLI

ρ_{avg} = Average settlement value observed from plate load tests based on weighted average considerations

SF = Settlement factor proposed by Madhav et al. (1999)

ρ_{tr} = Settlement of ground treated with RSCs

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