Settlement behaviour of a model footing on floating sand columns

La maniere d'echoument d'un modele a base sur les colonnes de sable flottantes

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ABSTRACT: Despite the developments in the theory and experimental methods in the last decades, floating sand/stone column subject is very scarce in the literature and there are still unclear and foregoing arguments about their reinforcing behaviour. To contribute to this subject, the load-settlement behaviour of a model square footing reinforced with sand columns having variable lengths on a soft clay soil of finite thickness was investigated through a set-up in the laboratory conditions. Settlement improvements within and under the sand column area, variation of stress concentration ratio for different column lengths, the mean vertical stresses under the sand column area and the effects of length/diameter and area replacement ratios to the settlement response of the reinforced soil were investigated. It has been found that, the presence of floating sand columns reduce the settlements in the reinforced clay zone as well as in the zone underneath the sand columns. The amount of settlement reduction in the unreinforced zone underneath the floating columns was found significant.

RÉSUMÉ: Malgré les développements dans la théorie et les méthodes expérimentales dans les derniers décades, le sujet des colonnes de sable/de pierre flottantes est très rare dans la littérature et il ya toujours des arguments précédents qui ne sont pas clairs à propos de leur conduite de renforcement. Pour contribuer à ce sujet, la manière d'echouement de la charge d'un modèle à base carré renforcé avec des colonnes de sable ayant des longueurs différentes sur un sol en argile molle d'une épaisseur limitée, a été recherché à l'aide d'une disposition dans les conditions de laboratoire. L'amélioration d'echouement à l'intérieur et sous la surface de la section de la colonne de sable, la variation du pourcentage de la concentration de la résistance interne pour les différentes longueurs des colonnes, la résistance interne verticale moyenne sous la surface de la section de la colonne de sable et les effets du pourcentage de replacement du longueur/diametre et surface à la réaction d'echouement du sol renforcé sont recherchés. Les recherches ont montré que la présence des colonnes de sable flottantes diminue les echouements dans la zone argile renforcée autant que dans la zone en-dessous des colonnes de sable. Le montant de la réduction d'echouement dans la zone renforcée en-dessous des colonnes flottantes est trouvé significatif.

1 INTRODUCTION

Floating sand/stone column subject is very scarce in the literature and there are still unclear and foregoing arguments about their reinforcing behaviour. To contribute to this subject, the load-settlement behaviour of a model square footing reinforced with 4 sand columns having variable lengths and diameters on a soft clay soil of finite thickness was investigated through a set-up in the laboratory conditions.

2 EXPERIMENTAL WORK

2.1 *Experimental Set-up*

An experimental set-up consisting of a test box, model footing, sand columns, loading mechanism, mini-settlement plates and dial gauges was designed and constructed (Figure 1).

Tests were performed in a test box of dimensions length:width:height = 330 mm:280 mm:140 mm. The model footing, 100 mm:100 mm:30 mm in dimensions, was made of hard wood for being light and strong against bending. It contained 4 holes of ϕ8 mm in diameter to allow placement of settlement measuring mini-plates. The holes, square in pattern, were opened 25 mm apart from the edges and 50 mm from each other. To measure the settlements in the various levels of sand columns together with the settlements under the sand column area, mini-settlement plates of ϕ20 mm and ϕ30 mm in diameter were used. Each sand column had one plate inside at a pre-determined level. These plates were connected to dial gauges by un-extensible ropes.

2.2 *Properties of the Sand and Clay Used in Experiments*

The sand used to form sand columns was the retaining sand between #20 and #30 sieves and were coarse to medium sand. The physical properties of the sand are presented in Table 1.

A number of triaxial tests were performed on sand samples with a representative density of ρ = 14.2 kN/m^3. The results are summarized in Tables 2 and 3. Test I and III have been conducted on 36.0 mm diameter samples, whereas Test II on 50 mm diameter samples.

The clay used was commercially available kaolinite type of remoulded clay. The white powder kaolinite clay was mixed

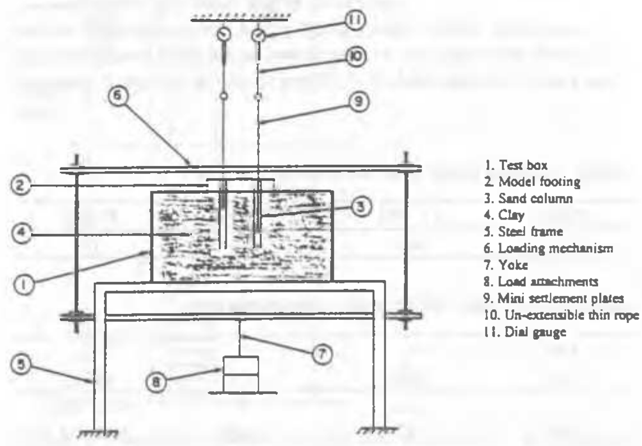

Figure 1. A descriptive diagram of the experimental set-up.

Table 1. Physical properties of the sand used in experiments.

USCS	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c	G_s
SP	0.582	0.640	0.740	1.27	0.95	2.67
	e_{max}	e_{min}	γ_{max} (kN/m^3)	γ_{max} (kN/m^3)		
	1.0	0.69	15.52	13.05		

Table 2. Elastic modulus (E_s) values of sand obtained from triaxial compression tests.

Test No.	Confining Pressure, σ_3 (kPa) 2	10	20	30	40
I	-	1250	12500	-	15000
II	-	1450	8800	13500	26000
III	300*	-	-	-	-

* E_s values in kPa.

Table 3. Internal angle of friction values of sand obtained from triaxial compression tests.

Test No.	I	II	III
ϕ (°)	40	50	60

with water (w_n = 34 %) to achieve the required consistencies of the clay soil to be used in the experiments. The Atterberg limits of the clay are summarized in Table 4.

Unconsolidated-undrained (UU) triaxial compression tests were performed on samples taken from the remoulded and compacted clays in which the sand columns were bored. The results are summarized in Table 5.

2.3 *Testing*

In this model study, tests were performed in 3 main groups. Group I consisted of 4 series of tests with different L/D ratio for ϕ20 mm sand columns. Similarly, Group II consisted of 4 series of tests with different L/D ratio for ϕ30 mm sand columns. And finally, Group III consisted of only 1 test with no sand columns present. The column diameter and the corresponding L/D ratios for each test are summarized in Table 6.

Clay was placed into the test box in layers by remoulding and placing by hand. Sand columns were formed by pushing a hollow brass pipe (ϕ20 mm/ϕ30 mm in diameter and 1.50 mm thick) into the clay soil very slowly until it reached to the required column depth. Then it was rotated around its axis to weaken its surface contact with the clay soil and with one thumb closing the upper part of the pipe to create a vacuum effect, it was pulled up again very slowly while rotating simultaneously. Sand was filled into the holes in layers, each layer being compacted for denser columns. While forming the columns, mini-settlement plates were placed at the pre-determined levels. Then loads were applied in stages and settlement measurements of the model footing and of different levels in the sand columns

Table 4. Atterberg limits of the kaolinite type of clay.

USCS	LL (%)	PL (%)	PI (%)
CL	42	23	19

Table 5. Results after (UU) triaxial compression tests.

Test No.	c_u (kPa)	ϕ_u (°)	E_u (kPa)
I	22	0	435 - 565
II	15	3.25	300 - 333
III	12	3.50	350 - 455

Table 6. Diameter and length of columns in the experiments.

Test No.	Column Diameter (mm)	Column Length (mm)	L/D Ratio
I	ϕ20	60	3
II	"	80	4
III	"	100	5
IV	"	140	End-bearing
V	ϕ30	60	2
VI	"	90	3
VII	"	120	4
VIII	"	140	End-bearing
IX	No column	-	-

were taken with respect to time. The duration for each load increment was 2 to 3 days.

3 EXPERIMENTAL RESULTS

The experimental results were presented as settlement versus time and settlement versus depth plots, of which two representative plots are shown in Figures 2 and 3.

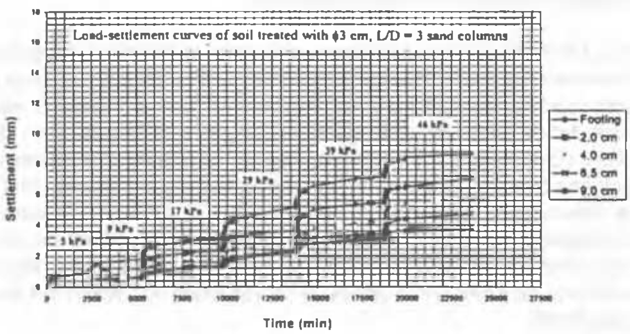

Figure 2. Settlement-time curves of footing and various points within the test box.

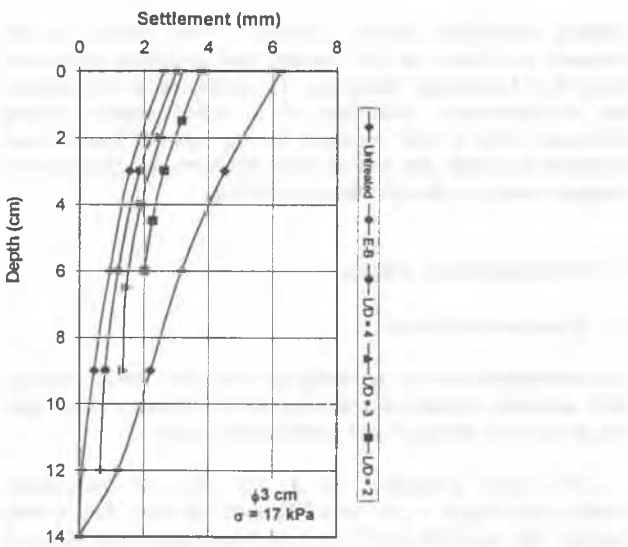

Figure 3. Settlement-depth plots of sand columns with various L/D ratios together with unreinforced footing.

4 EVALUATION OF EXPERIMENTAL RESULTS

4.1 *Settlement Reduction Ratio at Footing Level*

From the figures, of which a sample one is given in Figure 3, it was clearly seen that with increasing column length,

Table 7. β_f versus L/D relationship at footing level.

ϕ20 mm	L/D = 3	L/D = 4	L/D = 5	End-bearing
β_f	0.76	0.62	0.53	0.43
ϕ30 mm	L/D = 2	L/D = 3	L/D = 4	End-bearing
β_f	0.58	0.48	0.43	0.37

the settlements at the footing level decreased. This is also demonstrated by the settlement reduction ratio, β_f. Settlement reduction ratio is defined as the settlement of reinforced footing divided by the settlement of unreinforced footing.

β_f values were plotted with respect to column length in Figure 4 and tabulated as in Table 7. This figure shows that, the increase in column length causes a reduction in the β_f values. The β_f values are 0.58 and 0.75 for ϕ30 mm and ϕ20 mm diameter, 60 mm long sand columns respectively. These β_f values are reduced to 0.37 and 0.43 for end-bearing columns. The results also indicate that a reduction in the β_f values on the order of 40% occurs when short floating columns are compared to end-bearing columns.

The comparison of the β_f values for ϕ20 mm and ϕ30 mm sand columns in Figure 4 also indicates that higher area ratio (i.e. ϕ30 mm columns) reduces the settlements more effectively at shorter columns; and the difference in the β_f values for two area ratios considered, gradually decreases with increasing column lengths.

4.2 *Settlement Reduction Ratio along Column Length*

Settlement reduction ratio measured along the column lengths is denoted as β_c. The β_c values are tabulated as in Table 8 and the variation of β_c values with column length are presented in Figure 5, which is a sample one.

The comparison of β values in Tables 7 and 8 indicates that the surface values are equal or slightly higher than the values along column lengths. The β_f/β_c ratio varies in a range of 0.95-1.25.

4.3 *Settlement Reduction Ratio beneath the Treated Zone*

Throughout the experiments it has been observed that, the settlements measured in the clay situated below the sand columns are consistently smaller as compared to unreinforced footing settlements. This improvement in the settlements below the sand columns is illustrated in Figure 6. In this figure, s_1 corresponds to settlement of unreinforced footing and s_2 is the

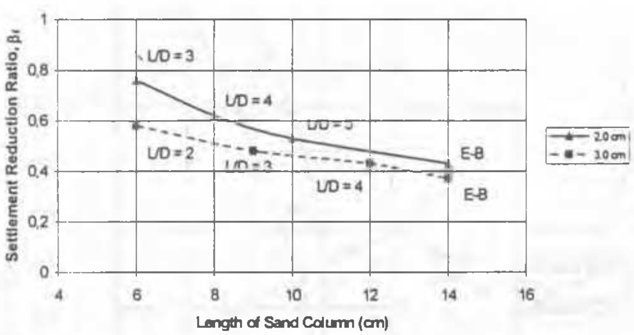

Figure 4. Comparison of β_f values for ϕ20 mm and ϕ30 mm sand columns.

Table 8. β_c versus L/D relationship along column length.

ϕ20 mm	L/D = 3	L/D = 4	L/D = 5	End-bearing
β_c	0.66	0.54	0.50	0.39
ϕ30 mm	L/D = 2	L/D = 3	L/D = 4	End-bearing
β_c	0.56	0.46	0.39	0.22

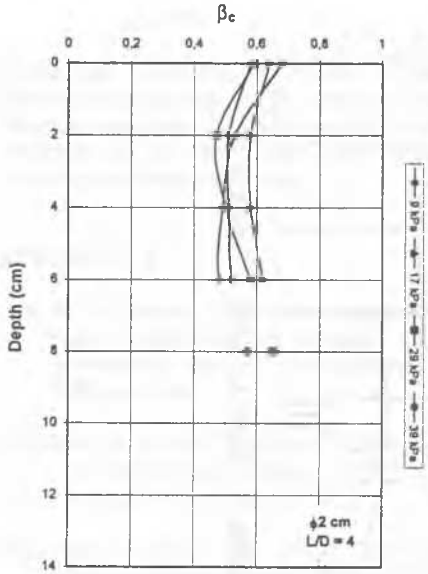

Figure 5. Variation β_c values along column lengths.

settlement of the reinforced footing below the treated zone. Then, a settlement reduction ratio is defined as $\beta_b = s_2/s_1$ for the clay layer below the treated zone.

The computed β_b values are given in Table 9. The comparison of β_b and β_f values indicates that, the β_b values are greater than the β_f values in general. The β_f/β_b ratio varies in a range of 0.70-1.07 for the majority of the data points.

Variations of β_b values for the untreated zone are plotted with respect to depth in Figure 7. The data trends indicate that, β_b values vary in a range of 0.50-0.75 with increasing L/D ratio.

Table 9. β_b versus L/D relationship along column length.

ϕ20 mm	L/D = 3	L/D = 4	L/D = 5
β_b	0.73	0.61	0.64
ϕ30 mm	L/D = 2	L/D = 3	L/D = 4
β_b	0.71	0.63	0.68

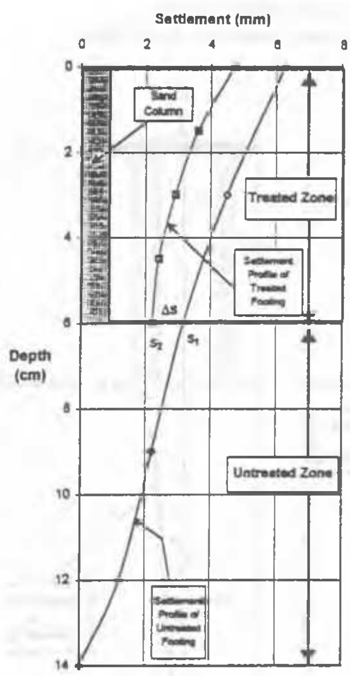

Figure 6. Descriptive sketch showing the improvement in settlements (data taken from ϕ20 mm, L/D = 3 ratio sand column under σ = 17 kPa).

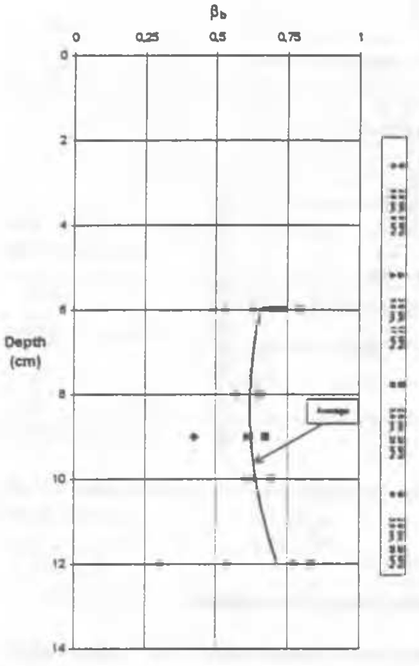

Figure 7. Variation of β_b values for the untreated zone.

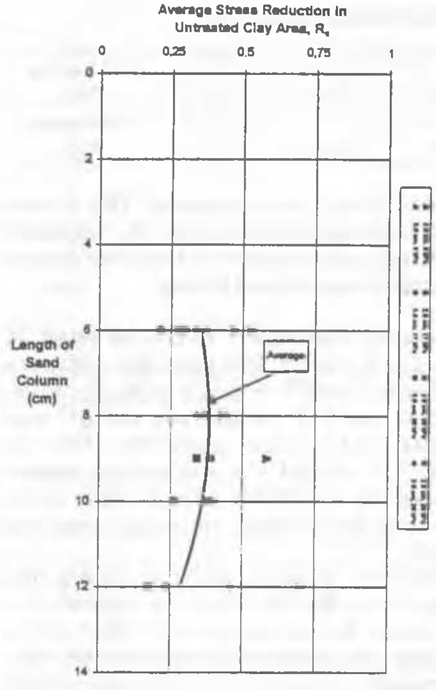

Figure 9. Variation of R_s values with the length of sand column.

Dependence of β_b on L/D ratio or area ratio could not be clearly demonstrated due to the scatter in the data trends.

The test results clearly show that, there is a net reduction in settlements in the untreated clay zone, below the sand columns as compared to unreinforced footing. It is anticipated that this improvement in the untreated zone is due to the reduction in vertical stresses arising from the presence of sand columns. This reasoning is made due to the fact that, the compressibility of the clay in the untreated zone remains unchanged; then the only factor affecting the settlement is the change in the magnitude of the stress increment.

In Figure 8, the settlement-depth plots for the unreinforced footing and soil with sand columns are shown. In this figure, the difference in the settlements, Δs arises from the reduction in the mean vertical stress, $\Delta\sigma$ in the untreated zone, due to the presence of sand columns which attract higher magnitude of vertical stress in the treated zone resulting from their higher stiffness. Then the ratio of $\Delta\sigma$ to the stress increase under the unreinforced footing below the treated zone is defined as the stress reduction ratio, R_s. The stress reduction ratio is calculated as; $R_s = \Delta\sigma/\sigma_1 = \Delta s/s_1$.

Figure 9 shows the variation of R_s values with the length of sand columns. It is seen from the random data trends that, the magnitude of R_s is independent of the area ratio and the R_s values are within a range of 0.25-0.50. Dependence of R_s on L/D ratio or area ratio could not be clearly demonstrated due to the scatter in the data trends.

4.4 *Stress Concentration Ratio*

Stress concentration ratio, n values have been obtained from the measured data by means of the correlations present in the literature (Aboshi et.al., 1991). The calculated average

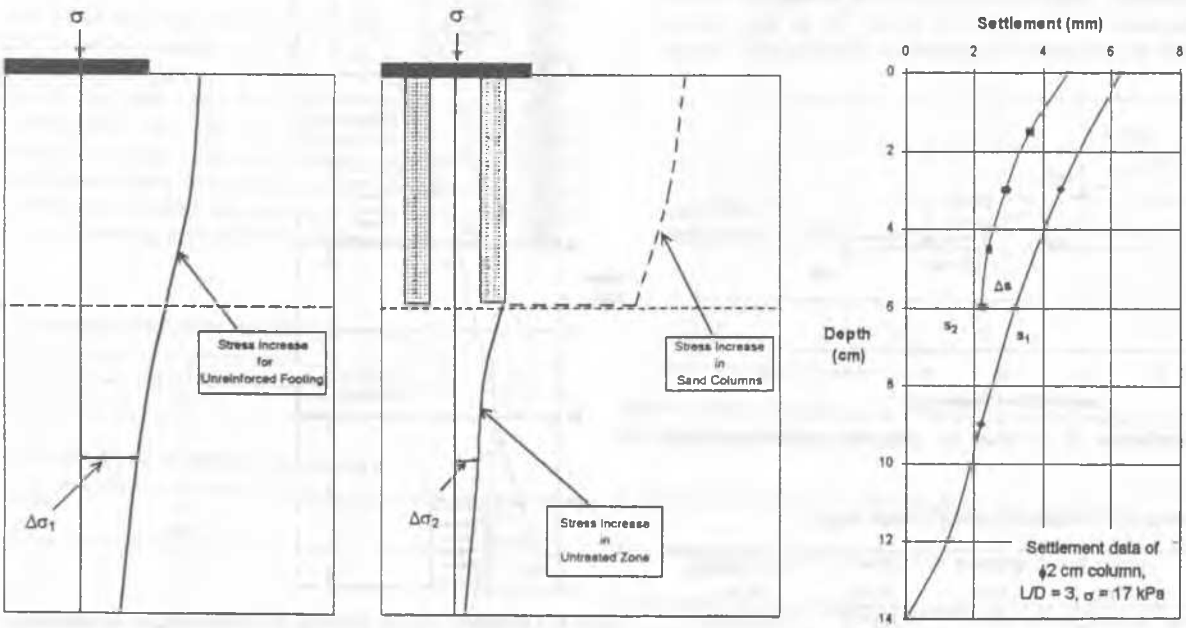

Figure 8. Descriptive sketch of R_s.

Table 10. The average stress concentration ratios.

ϕ20 mm	L/D = 3	L/D = 4	L/D = 5	End-bearing
n	3.51	5.76	7.26	11.83
ϕ30 mm	L/D = 2	L/D = 3	L/D = 4	End-bearing
n	3.45	4.34	5.13	7.34

stress concentration ratios are tabulated in Table 10 and the variations of n with column length are shown in Figure 10.

$$\beta = 1 / [1 + (n - 1) . a_s]$$

From Figure 10, it is seen that ϕ20 mm (a_s = 0.126) columns take higher proportion of the applied stress than ϕ30 mm (a_s = 0.283) columns. Stress concentration ratio increases as the column length increases. The increase in n value is more pronounced in ϕ20 mm columns than the ϕ30 mm columns.

4.5 *Deformation Modulus of Untreated and Composite Soils*

The measured settlements were evaluated to back-calculate the drained deformation modulus values for the unreinforced soil. Evaluation of the unreinforced footing settlement data reveals that, the drained value of clay soil is E_d = 188 kPa in average.

The measured settlements were also evaluated to back-calculate the drained deformation modulus values for the composite soil. The deformation modulus values have been found to change linearly with the increasing L/D ratio as shown in Figure 11. Since E_{clay} is constant, the linear increase of the composite soil E_d value can be attributed to the increase in E_{sand}. In this study, the ratio $E_{composite}/E_{sand}$ changed from 1.50 to 2.50 in average for the shortest and end-bearing sand columns, respectively.

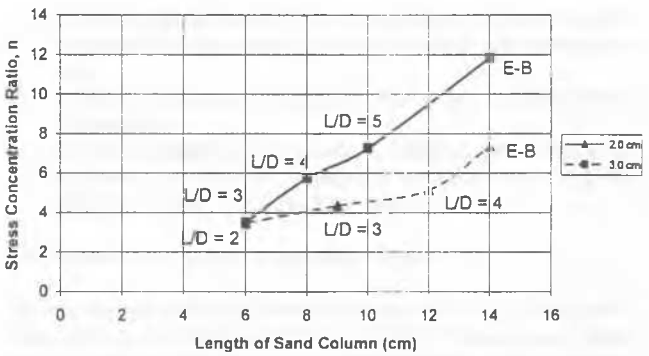

Figure 10. Variation of average n values with column length.

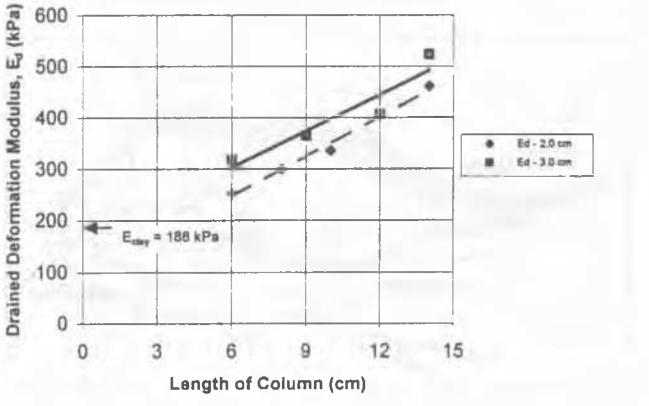

Figure 11. Variation of deformation modulus values with column length.

5 CONCLUSION

It has been found that, the presence of floating sand columns reduce the settlements in the reinforced clay zone as well as in the zone underneath the sand columns. The amount of settlement reduction in the unreinforced zone underneath the floating columns was found significant.

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