A model study of strains under footings supported by floating and end-bearing granular columns

Une étude sur modèle réduit des contraintes sous semelles isolées reposant sur des colonnes granulaires flottantes et encastrées

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ABSTRACT: A model study was performed in order to examine settlements in the presence of floating and end-bearing granular columns and without columns (untreated) under D=100 mm and D=200 mm circular loading plates (footings). It is aimed to find effective length in floating type granular columns that provides significant settlement improvement under footings. In addition to total footing settlements recorded by displacement transducers, subsurface displacements both along the column and in the untreated soil below column were measured by miniature borehole settlement gages for different column lengths and loading plate diameters. Settlements and strain distributions obtained from displacement measurements with depth show the role of column length in settlement reduction.

RÉSUMÉ : Une étude sur modèle réduit a été réalisée pour examiner les tassements du sol en présence ou non de colonnes granulaires flottantes et encastrées, sous des plaques de chargement circulaires de diamètre D=100 mm et D=200 mm (semelles isolées). Le but est de trouver la longueur optimale des colonnes granulaires flottantes permettant d'obtenir une amélioration significative des tassements sous semelles. Pour différentes longueurs des colonnes et différents diamètres de fondations, les tassements des semelles ont été enregistrés à l'aide des transducteurs. En plus de ces enregistrements, les déplacements en profondeur, le long des colonnes et en dessous de celles-ci ont été mesurés par des gauges miniatures. Les tassements et les distributions des contraintes déduits des enregistrements de déplacements en profondeur ont montré le rôle de la longueur de la colonne dans la réduction des tassements.

KEYWORDS: model test, granular column, floating stone column, settlement, subsurface displacement

1 INTRODUCTION

Granular columns as semi-rigid inclusions are used to reduce settlements under foundation loads in compressible soils. The column length is a significant design decision in settlement reduction in deep compressible soils.

An experimental research was performed to find out an effective length in floating type columns to get benefit of them as settlement reducers.

2 LABORATORY TESTS

2.1 Material Properties

The model tests were carried out in loading tanks designed as large oedometers (d=410 mm, h=390 mm). The clay 'foundation' soil loaded in model test was obtained by consolidating commercially available remoulded kaolinite type clay from paste (moisture content w=42 %) inside the loading tank under a pressure of σ_v=50 kPa. Kaolin clay has a plasticity index of PI=22 % (liquid limit, LL=51% and plastic limit, PL=29 %). Plasticity of kaolin eliminates swelling and shrinkage problems.

Foundation soil has an average undrained shear strength of c_u=25 kPa. Coefficient of compressibility, m_v values for the pressure intervals in main tests are given in Table 1.

Granular columns with a relative density of 80 % were formed by compacting sand material. Grain size distribution of the sand has been arranged based on Dc/D (column diameter/typical particle size) ratio in stone column applications. The grain size distribution and physical properties of sand are shown in Table 2 and Table 3 respectively.

Table 1. Laboratory consolidation test results of clay foundation soil

Test No	*50-75 kPa* *mv (m^2/kN)*	*75-100 kPa* *mv (m^2/kN)*
Test No:1	0.000409	0.000324
Test No:2	0.000442	0.000345
Test No:3		0.000363

Table 2. Grain size distribution of sand used in granular column

Sieve #	*D(mm)*	*Percent finer than D(%)*
50	0.315	100
70	0.210	70
100	0.149	38
200	0.074	6
325	0.035	0

Table 3. Physical properties of sand with relative density of 80%

USCS	e_{min}	e_{max}	G_s	ϕ^0
SP	0.961	0.581	2.683	42

2.2 Experiment Set-Up and Test Procedure

Following the completion of consolidation inside loading tank, clay foundation height is fixed to H=290 mm by removing some soil at the top. To form granular columns, soil was drilled by 20 mm auger to the desired depth with the aid of steel template placed on soil and then the bored hole was filled with sand and rammed in a controlled manner to have a relative density of 80% throughout the column length. In each test, two granular columns were instrumented for subsurface settlements, the central column and one of the closest columns to the centre. Drilling of instrumented columns was done throughout the foundation soil (290 mm).

A miniature magnetic switch apparatus has been developed based on the measurement principle of magnetic extensometer to get subsurface displacements (Tekin 2005). The apparatus consists of an antenna rod with a base, ring type magnets, magnetic switch probe and a worm gear device designed to move the probe inside the antenna rod slowly. After drilling, long antenna rod (d=6 mm) was inserted into this hole and its base was placed at the bottom of the tank. The gap between the bored hole and outer surface of antenna rod was filled with sand or clay till the desired level of settlement measurement. Then ring type magnet (d=13 mm) was passed through the rod. At least eight magnets were placed along 290 mm depth. A hollow ramming device was used to compact sand at the same relative density of other columns and for compression of clay.

When all columns were prepared, the surface was flattened; loading plate and loading frame were mounted. Two displacement transducers were located on the loading plate to record plate settlement (total footing settlement). Initial (reference) magnet locations were determined by moving the probe slowly inside antenna rods.

Footing load of 75 kPa was applied on clay soil improved by granular columns. At the end of consolidation (test), final readings were taken throughout the antenna rods.

In the test series with 200 mm plate, at the end of 75 kPa loading, test was repeated for 100 kPa loading with settlement measurements. Figure 1 shows experimental set-up.

Tests without granular column installation (untreated soils) but with the same loading levels and instrumentation were done for each loading plate diameter. These reference tests were the basis of comparisons to find out the contribution of granular columns to settlement reduction for different column lengths.

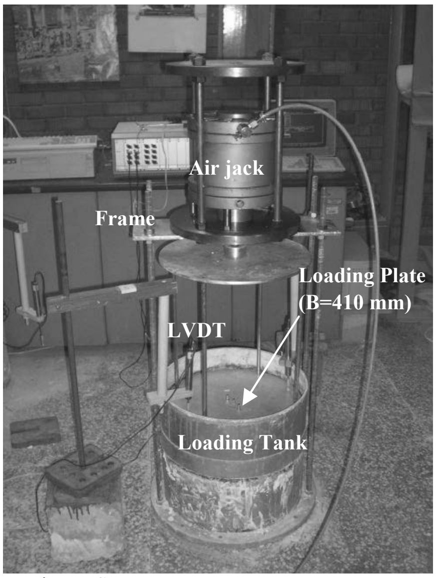

Figure 1. Experiment Set-Up

3 TEST RESULTS

Scope of this research involved not only the efficiency of floating granular column length but also effect of column number (area replacement ratio) and comparison of end-bearing columns for footings (B=100 mm, B=200 mm) and 1-D unit cell (B=410 mm) concepts on settlement improvement. Column length, loading plate diameter, area replacement ratio and loading levels were the variables, but clay thickness (H=290mm) and column diameter (20 mm) were kept constant in all tests. However, this paper includes only the behavior of floating granular columns loaded under B=100 mm and B=200 mm plates, therefore only related test series and their findings were given in this paper. The details of the test series selected are summarized in Table 4. Area replacement ratio is 0.22 in all tests. End bearing series in Series III are also included.

Table 4. Summary of test results

Series No	*Loading Plate Diameter B(mm)*	*Applied Pressure (kPa)*	*L (mm)*	*L/B*
I	100	75	Untreated (no columns)	
III	100	75	60	0.6
			100	1.0
			140	1.4
			210	2.1
			290 (eb)	2.9
IV	200	75,100,125	Untreated (no columns)	
V	200	75,100	100	0.5
			140	0.7
			200	1.0
			275	1.375

In series I and III, the ratio of clay height (H=290 mm) to plate diameter (B=100 mm) is H/B=2.9. Due to the limitation in tank height, H/B ratio is 1.45 (H=290 mm/ B=200 mm) in Series IV and V. There may be some boundary effects in Series IV and V due to lower H/B ratio. However they do not influence the general trend of displacements and strain behavior encountered both along the columns and the clay layer underlying columns. Similar results have been found for floating columns both in B=100 mm and B=200 mm tests.

As seen in Figure 2 and Figure 3, cumulative displacements occurring within the clay layer underneath column decrease significantly in the columns longer than L/B=1.0.

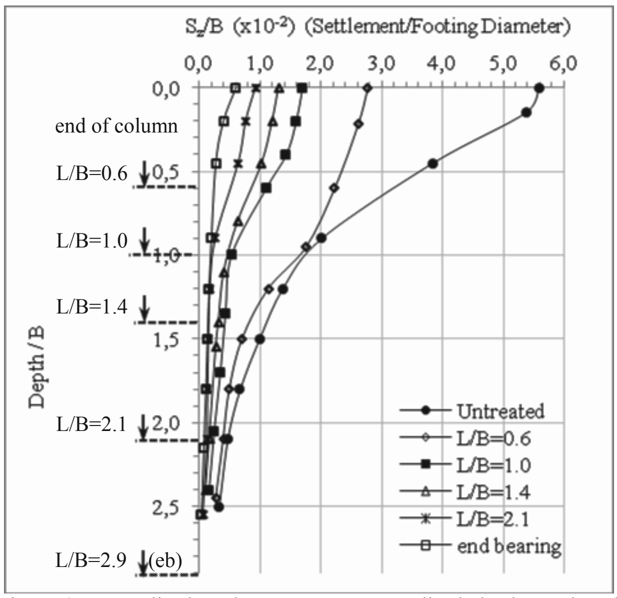

Figure 2. Normalized settlement versus normalized depth graphs of Series I and III (B = 100 mm, 75 kPa)

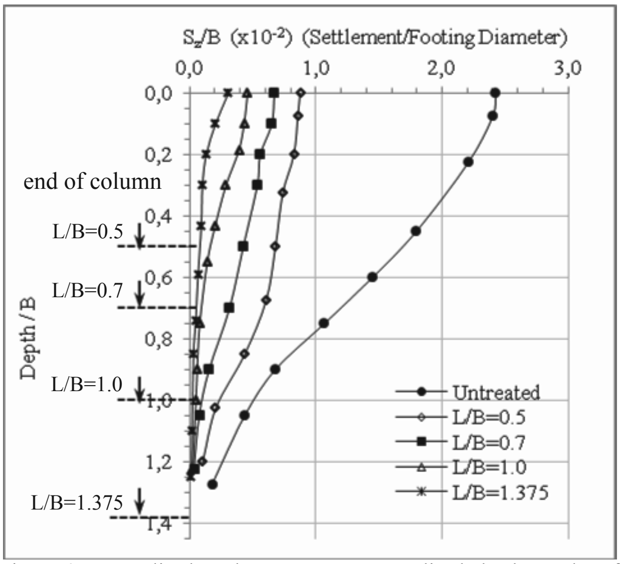

Figure 3. Normalized settlement versus normalized depth graphs of Series IV and V (B = 200 mm, 75 kPa)

The strains at every cm depth interval are determined from the settlement-depth graphs obtained with LVDT and miniature magnetic switch apparatus measurements and then plotted as strain vs. normalized depth graphs as illustrated in Figure 4 and Figure 5.

In floating granular columns, the efficiency of column length of L/B=1.0 to 1.2 is observed in strain vs. normalized depth graphs shown in Figure 4 and Figure 5. It is obvious that they reduce the strains considerably throughout their length when compared to those in the untreated case. They also manage to decrease the strains in underlying clay layer significantly.

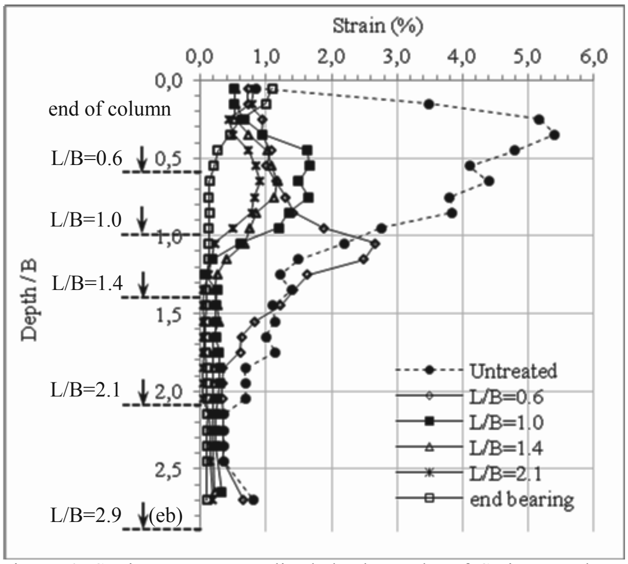

Figure 4. Strain versus normalized depth graphs of Series I and III (B = 100 mm, 75 kPa)

However, a trend of increasing strains is observed in clay layer starting from the end of column under the columns shorter than L/B=1.0. Strains make a peak and then decline (L/B=0.6 with B=100 mm plate and L/B=0.5 and L/B=0.7 with B=200 mm plate). In the test Series III (B=100 mm) with L/B=0.6 these peak strains are even higher than those in the untreated case for the same depth. All the findings show that the columns shorter than L/B=1.0 are not adequate to reduce the strains in clay layers underlying floating type granular columns.

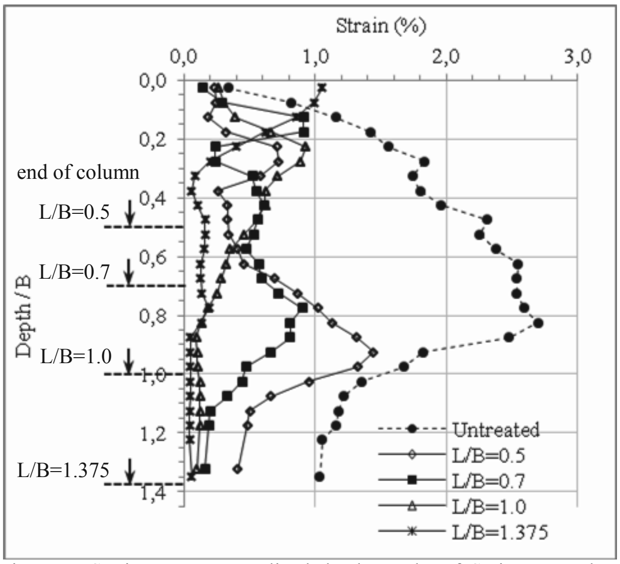

Figure 5. Strain versus normalized depth graphs of Series IV and V (B = 200 mm, 75 kPa)

Uppermost 0.2B to 0.3B depth of columns are strained in end bearing columns, then strain value decreases and keep constant till the end of column. The columns with L/B=1.375 in test series V can also be considered as end-bearing columns.

Ratio of the strain values in the columns to those in the untreated clay at the same depth are presented in Figure 6 and Figure 7. Effectiveness of the ratio L/B=1.0 to 1.2 is again clear. Strain ratios under short columns with L/B<1.0 length are nearly the same as those in the untreated condition, in other words L/B<1.0 column length is insufficient for settlement reduction.

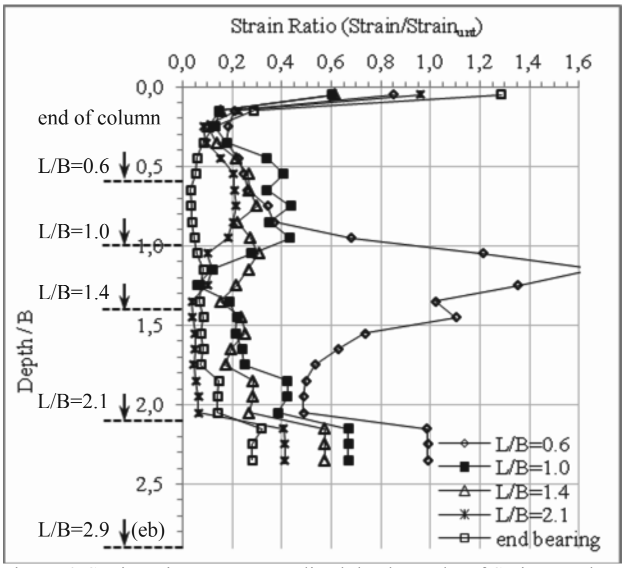

Figure 6. Strain ratio versus normalized depth graphs of Series I and III (B = 100 mm, 75 kPa)

In columns with L/B>1.0 length, columns contribute to strain reduction in the clay soil underneath till 2.0 B depth. The increase in strain ratio after 2.0 B implies that cumulative settlement decreases considerably below 2.0 B in the untreated cases so that any improvement effort has no contribution to settlement reduction below this depth. This also explains similarities in the behavior of L/B=2.1 floating and end bearing columns.

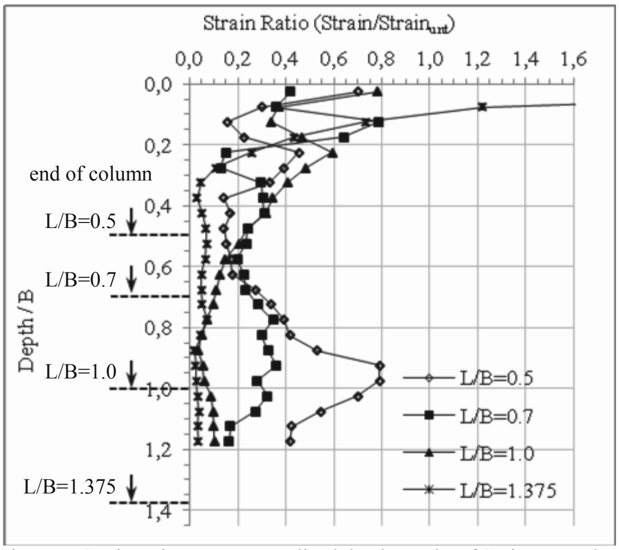

Figure 7. Strain ratio versus normalized depth graphs of Series IV and V (B = 200 mm, 75 kPa)

Figure 8 and Figure 9 are the graphs of settlement reduction factor β with depth, in other words the cumulative settlement ratio of improved to untreated soil at any depth. Similar behavior to variation of strain ratio above is observed.

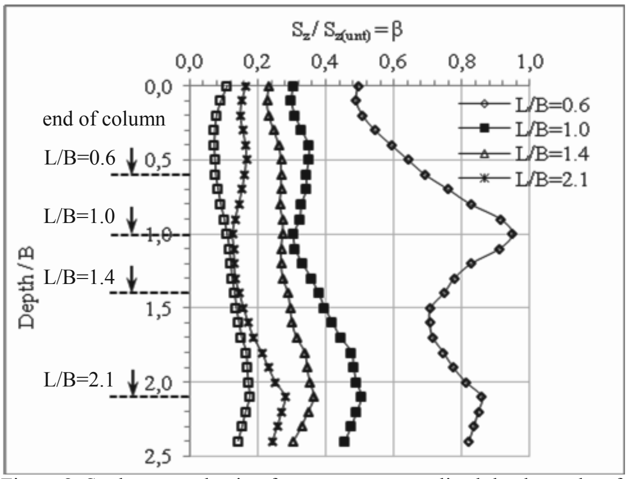

Figure 8. Settlement reduction factor versus normalized depth graphs of Series I and III (B = 100 mm, 75 kPa).

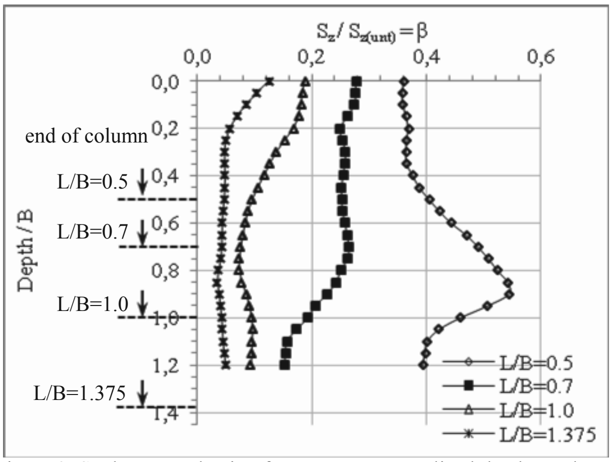

Figure 9. Settlement reduction factor versus normalized depth graphs of Series IV and V (B = 200 mm, 75 kPa)

Settlement reduction factors along the columns are almost the same as those measured in total settlements (cumulative settlement) for L/B > 1.0 in all floating type granular columns (Figure 10). Settlement reduction factors in the underlying clay soil are also similar for lengths of L/B >1.0 but it is much higher (0.7) for L/B=0.6 which means poor improvement.

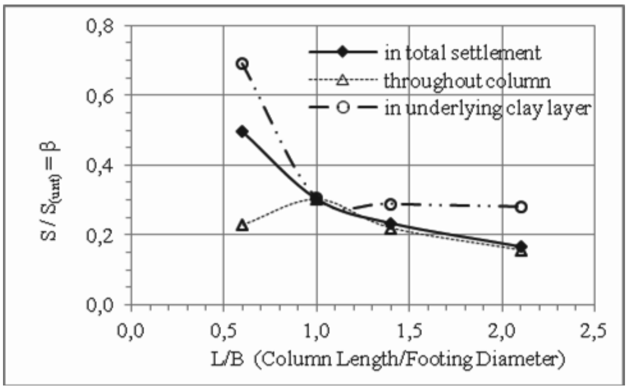

Figure 10. Settlement reduction factor graphs of Series I and III (B = 100 mm, 75 kPa)

4 CONCLUSIONS

Strains measured along granular columns and below in clay under loaded circular plates indicate the following:

a) Strains are small below granular columns whose length is roughly equal to side dimension of the plate (L/B=1.0-1.2). This explains why floating columns are effective in ground improvement.
b) Strains below short columns in clay with L/B<1.0 show an increase and a peak indicating probable high stress transfer through columns. Improvement by short granular columns is limited.
c) Longer columns with L/B>2.0 show similar behavior to end bearing columns (i.e. very limited displacement)

Settlement reduction factors decrease with increasing column lengths. These factors along the columns are similar to the factors below the columns for lengths L/B>1.0.

5 REFERENCE

Tekin M 2005. *Model study on settlement behavior of granular columns under compression loading*. Ph.D. thesis submitted to the graduate school of natural and applied sciences of Middle East Technical University Ankara TURKEY, 223 pages.