The use of sand columns to improve soft soil

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Abstract

This investigation describes the efficiency of using sand columns in improving soft clayey soils. Variables such as reinforcement ratio (number and cross section of sand column)and relative density of column material and their effect on the new soil system were studied. The effect of the loading area and length of column penetration is studied also.

To achieve the above aims, a detailed laboratory investigation was carried out on sand column reinforced soil using a series of triaxial tests on the composite specimens and performing laboratory plate loading tests on models of single sand column in soft clay.

The test results highlight the effect of the various parameters that affect the performance of the sand column and provide fundamental points govern the behaviour. Simple and useful chart is also suggested as a guide for estimating the reinforcement requirements for a given soil improvement demand.

Keywords

Sand column, soft soil, soil improvement.

Introduction

Among the several methods applied in ground improvement the compacted granular column has been increasingly used during the past three decades as a technique to reinforce soft and very soft compressible clays, silts for loose silty sands . This is because it represents the cheaper way among the other methods. The material used is cheep and the technique is simple. The concept of using granular piles was first applied in France in 1830 by French military engineers to improve a native soil.

According to the grain size of column material, granular columns may be divided into two categories; stone and sand columns. Both of the two types can improve the soft soils by increasing load bearing capacity, accelerating consolidation process and reducing the final settlement of the soft soil.

Theoretically, sand columns improve foundation bearing capacity because they are stiffer than the material which they replace (Al-Kafaji, 1996). Both column and surrounding soil have a mutual effect to increase the bearing capacity of the improved ground. The compacted sand pile takes its shear strength from lateral support provided by the surrounding soil like the action of chamber pressure in triaxial cell.

Greenwood, (1970) was one of the first who came up with mechanisms and explained the load transfer phenomenon in granular column, (Rao, 1997). He assumed that the column is loaded triaxially, used Bell's (1915) theory for passive pressure in the estimation of the radial stress and quoted the following formula to estimate the ultimate load capacity of a single column.

$$\sigma_{cu} = K_{pc} * (2C_u + \sigma_{ro}) \quad \text{...(1)}$$

Where,

σ_{cu}: Ultimate vertical stress carried by the granular pile.
K_{pc} : Rankine passive pressure coefficient for the column material.
σ_{ro}: Initial in situ radial stress.

Based on the laboratory model experimental results obtained by Hughes and Withers, (1974), they concluded that the ultimate strength of the column is governed by the limited maximum lateral resistance of the soil around the column during bulging, in other words, the sand column can be thought of as being confined in a triaxial stress system where the cell pressure is limited. The authors presented their method of analysis that was developed from the results of plasticity theory from which the limiting stress is given by Gibson and Anderson in 1961 as:

$$\sigma_{rL} = \sigma_{ro} + c\left[1 + \ln\left(\frac{E}{2c(1+\mu)}\right)\right] \quad \text{..............................(2)}$$

Where, σ_{ro}, E, μ & c: are respectively, the total in situ lateral stress, the elastic modulus, Poisson's ratio and the undrained cohesion.

Al-Khafaji, (1996) examined the use of the sand compaction pile for reinforcing soft clay ground through using the centrifuge modeling technique. The major part of the study was concentrated on the settlement reduction obtained improvement and the following empirical equation.

$$S_c = 2.1 * \ln\left(\frac{E_c}{E_s}\right) - 2.1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

In which E_c&E_s = are the modulus of elasticity of column material and soil respectively.

Laboratory work

Three types of soils were used in this study; kaolin clay for the soft media, natural sand and gravel to be used in the construction of columns. Two molds were designed and manufactured for this purpose to produce 100 mm annular soft clay samples to be tested in triaxial apparatus and to prepare soft clay beds required in model testing program. See Fig.(1) and Fig.(2).

Kaolin slurry was prepared by well mixing of kaolin powder passing no. 40 sieve with a certain amount of water that give the slurry twice the liquid limit. The slurry was then left in airtight container for (5-6) days to ensure the full saturation of kaolin particles. The slurry was poured in one of the molds shown in Fig.(1) and Fig.(2) and left under a consolidation stress of 100 kPa for about (130-140) hours. The sand or gravel column was installed in the middle of soft samples driving a thin-walled brass tube and draw it carefully to form a hole of the required diameter. The hole was then, backfilled with column material (sand or gravel) in five successive layers each layer was compacted with a light steel rod to get the required relative density.

Testing programme

Eleven CU-triaxial compression tests were performed to cover the studied parameters (reinforcement ratio a_s and relative density of column material D_r). Three values of reinforcement ratio were taken 1/16, 1/7 and 1/4. Also, three values of D_r were considered 20%, 60% and 85% for each selected reinforcement ratio. The consolidation pressures were 100, 200 and 300 kPa.

The model testing procedure was carried out according to ASTM D1194-72 Standard on eleven models to study the following variables:

a. The ratio of loading area to the cross-sectional area of the sand column (A_p/A_s). Four values were chosen.
b. The length of the column to its diameter ratio (L/D). Four values were taken 7, 6, 4 and 2.
c. The relative density of the sand column (D_r) 20%, 60% and 85%.

Results and discussion

Results of triaxial tests

Figure (3) shows the results of CU-triaxial compression test on 100mm composite sample of soft kaolin clay reinforced by 37.5mm sand column with D_r=85% (as an example for all tests on composite samples).

To show the effect of reinforcement ratio (a_s) on the performance of sand column in soft clay, the factor (F_d) was introduced and obtained from:

$$F_d = \frac{\max.(\sigma_{1r})}{\max.(\sigma_{1ur})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

Where, σ_{1r}, σ_{1ur}=Total axial stress of reinforced and unreinforced sample.

Table (1) shows the effect of both a_s and D_r on the values of F_d.

Also, the effect of both variables on the normalized undrained shear strength $\left(\frac{S_u}{\sigma'_c}\right)$ can be seen in Fig.(4).

In order to show the improvement gained using sand column a factor F_r is introduced and defined as:

$$F_r = \frac{(S_u)_{re\inf.soil}}{(S_u)_{unre\inf.soil}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where, S_u=is the undrained shear strength.

Similar to Fig.(4), Figure (5) is formed which the relationship between F_r, a_s and D_r can be obtained as follows:

$$F_r = 1 + C_1 * a_s + C_2 * a_s^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Where,

$$C_1 = 2.576 - 21.23 * D_r + 18.61 * D_r^2$$

$$C_2 = -13.02 + 153.74 * D_r - 87.96 * D_r^2$$

The range of application of Fig. (5) can be extended by substituting another values of a_s and D_r and calculating the corresponding F_r from Equation (6). Fig. (6) presents the results as a design chart from which an assessment of the improvement method can be obtained. This figure is useful to some extent to estimate the required reinforcement ratio or volume of sand replacement per cubic meter of untreated land for a given improvement requirement and specified relative density of sand used in the column.

Results of model tests

The ratio of ultimate bearing capacities of treated to untreated soil (q_{ur}/q_u) was decreased with the increasing in the ratio of loading area to the area of sand column used (A_p/A_s). This result may be supported by the following equations with aid of Fig. (7).

$$P = P_S + P_C \quad \text{...(7)}$$

$$\sigma * A_P = \sigma_S * A_S + \sigma_C * A_C \quad \text{..(8)}$$

where, A_c: loaded area of clay , $A_C = A_P - A_S$

$$\therefore \sigma * A_P = \sigma_S * A_S + \sigma_C * (A_P - A_S) \quad \text{...........................(9)}$$

$$\text{Or, } \frac{\sigma}{\sigma_C} = \frac{\sigma_S}{\sigma_C} * \frac{A_S}{A_P} + \frac{A_P - A_S}{A_P} \quad \text{...................................(10)}$$

But, $n = \frac{\sigma_S}{\sigma_C}$ is concentration ratio.

$$\text{Thus, } \frac{\sigma}{\sigma_C} = 1 + \frac{A_S(n-1)}{A_P} \quad \text{...(11)}$$

At failure, $\frac{\sigma}{\sigma_C}$ is approximately equal to (q_{ur}/q_u). Hence, (q_{ur}/q_u) is decreased with increasing of (A_p/A_s) keeping (n) unchanged.

It was found that with increasing of (L/D) ratio, the (q_{ur}/q_u) ratio was increased. For example, when (L/D) changed from 2 to 4 the ultimate bearing capacity of reinforced soil increased 2 folds. This may be related to the following:

1. When the column is floating in the soft clay (i.e. L/D < 7) the stresses at the tip of the column can not be reflected above, but dissipated in the soft clay.
2. The granular column takes its capacity from bulging which is usually happened in long columns. Short columns rarely exhibit this phenomenon and may be considered as a short pile.

Conclusions

1. The undrained shear strength of reinforced sample (S_u) was found to be depended on both reinforcement ratio a_s and relative density of the sand in the column D_r. The improvement gained was highly affected by the number of sand columns used rather than the relative density of soil in the column.
2. The increase in bearing capacity is inversely proportional with the ratio of footing area to the sand column cross-sectional area (A_p/A_s) and directly with L/D ratio and relative density of sand.
3. The reduction in settlement is affected in the same manner mentioned in point 2 above.

References

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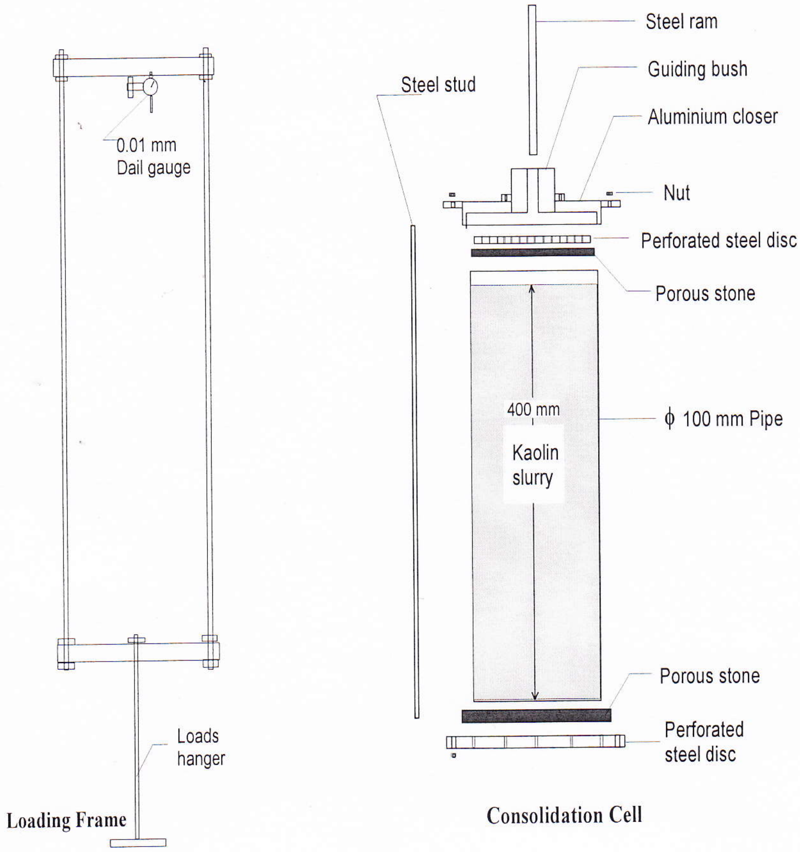


Figure (1): Φ 100mm consolidation apparatus

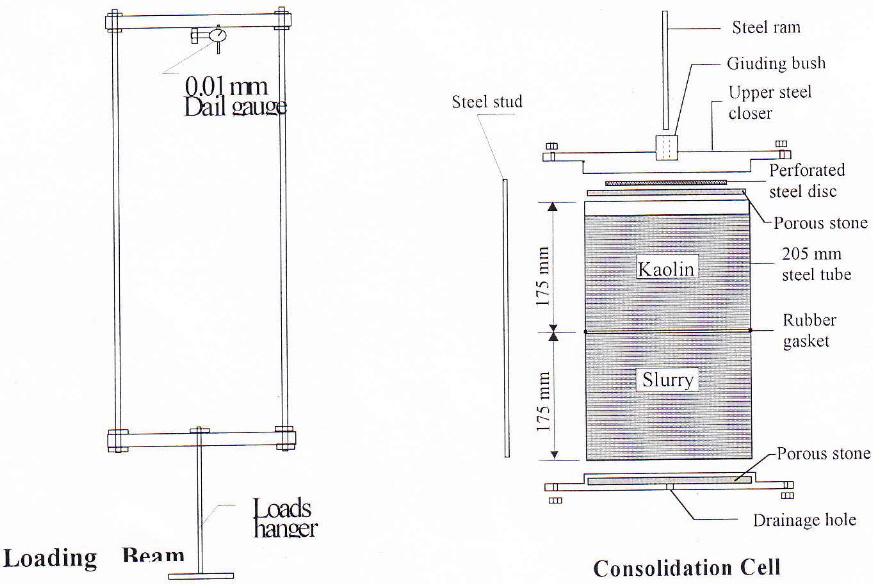
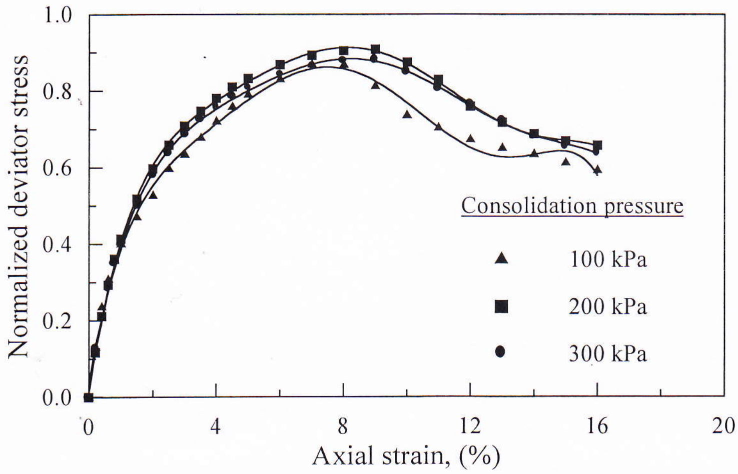
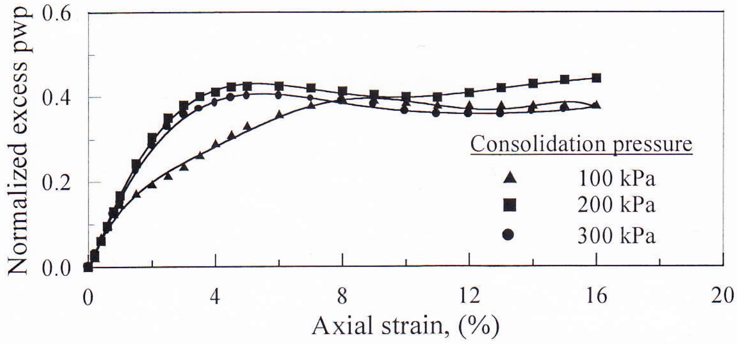


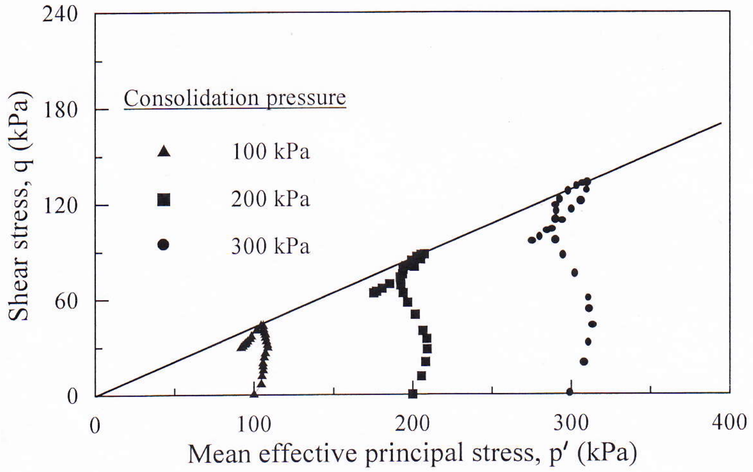
Figure (2): Soft clay bed preparation



A: Normalized Deviator Stress-Strain Relationship



B:Normalized Excess PWP-Axial Strain Relationship



C: Effective Stress Paths

Figure (3): CU-Triaxial compression test results

Table (1): Effect of a_s on values of F_d

Reinforcement ratio (a_s)	Values of F_d								
	D_r = 20 %			D_r = 60 %			D_r = 85 %		
	σ'_c=100 kPa	σ'_c=200 kPa	σ'_c=300 kPa	σ'_c=100 kPa	σ'_c=200 kPa	σ'_c=300 kPa	σ'_c=100 kPa	σ'_c=200 kPa	σ'_c=300 kPa
1/16	1.03	1.01	1.01	1.08	1.08	1.08	1.121	1.12	1.14
1/7	1.04	1.03	1.03	1.14	1.12	1.12	1.25	1.26	1.24
1/4	1.22	1.20	1.20	1.63	1.37	1.52	2.15	2.10	1.89

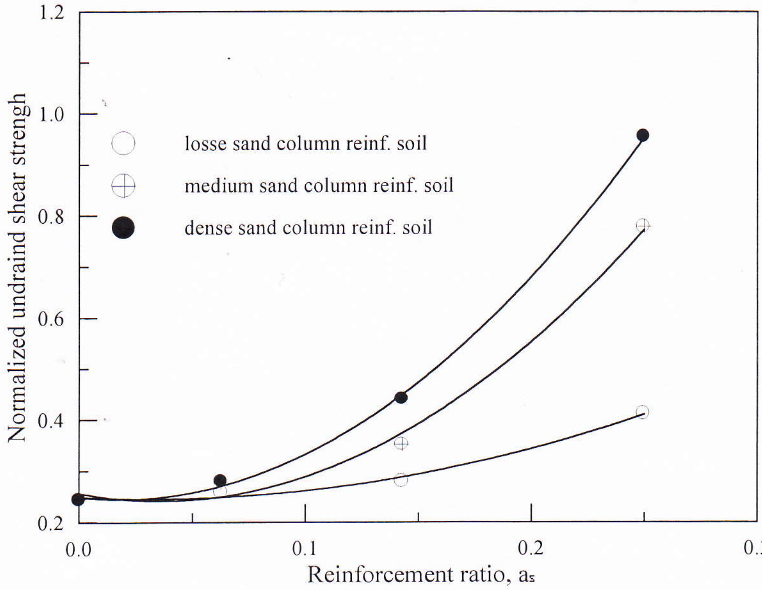


Figure (4): Relation between Normalized Undrained Shear Strength and Reinforcement Ratio for Different Relative Densities of Sand in the Column

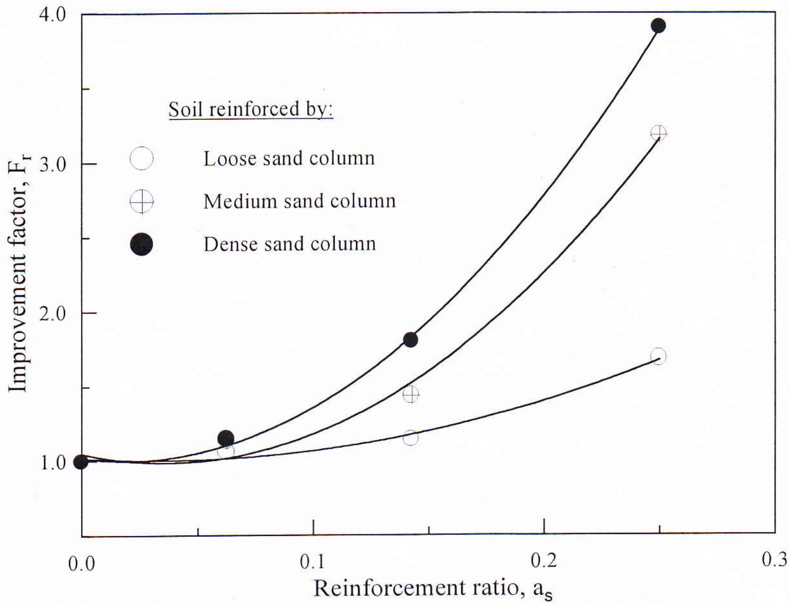


Figure (5): Relation between Improvement Factor and Reinforcement Ratio for Different Relative Densities of Sand in the Column

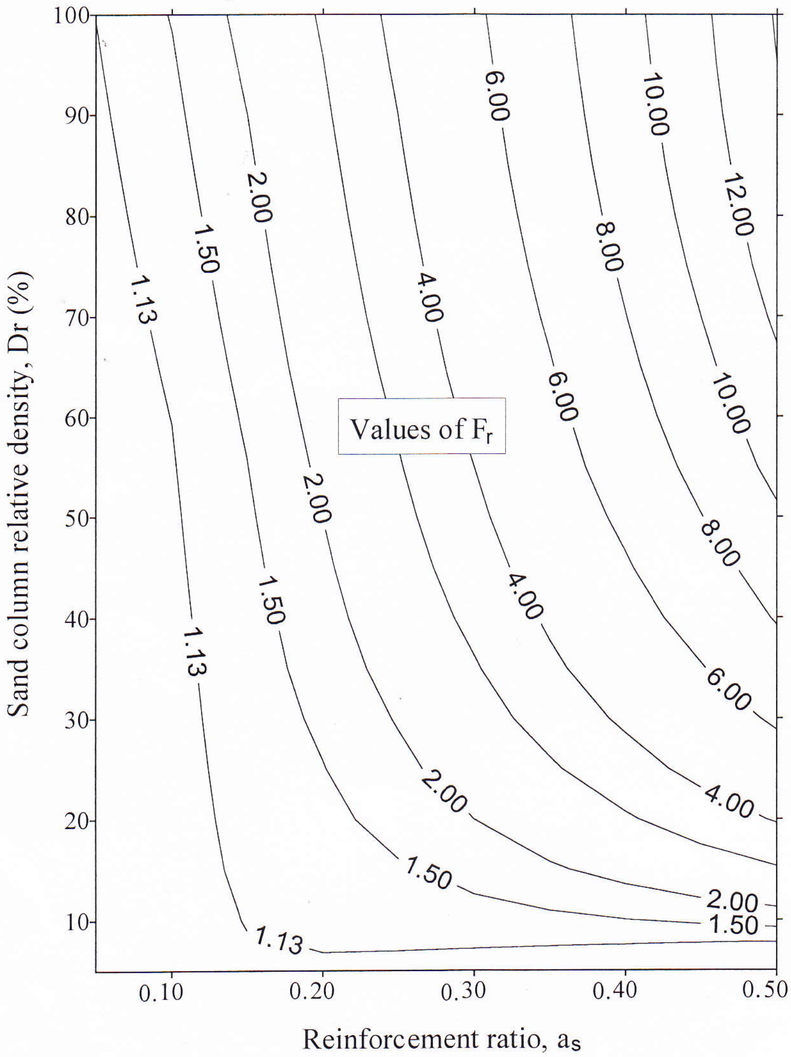


Figure (6): Prediction of Improvement Factor F_r

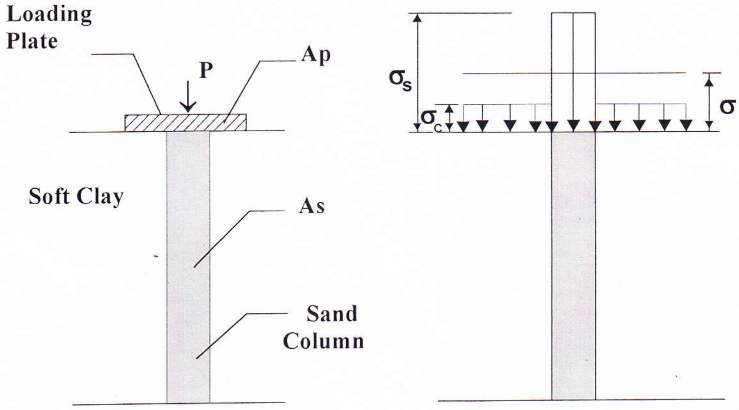


Figure (7): Analysis of Stresses in Sand Column Model