Sand Column Stabilized by Silica Fume Embedded in Soft Soil

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ABSTRACT

This research aims to study the behavior of the sand columns stabilized with silica fume (as an additive with different percentages) and driven in soft soil bed with un drained shear strength (c_u) between 16 – 21 kPa. Holesin the shape of columns with diameter 50 mm and length 300 mm have been drilled in a soil bed and backfilled with sand mixed with several proportions of silica fume with 7-days curing. A rigid circular footing with diameter 64.6 mm was located on each column and loaded axially till failure. The results analysis of the model tests indicated an encouraging improvement in load carrying capacity of the columns and considerable reduction in the settlement compared to the conventional stone columns. The bearing improvement ratio and settlement reduction ratio exhibited by the sand columns are 1.18 and 0.71, respectively. The best possible addition of silica fume content in sand–silica fume columns is 7% giving bearing improvement ratio and settlement reduction ratio of 1.56 and 0.5 respectively.

Keywords: Sand Columns; Silica Fume; Improvement; Soft Soil

INTRODUCTION

Sand and stone column, known as column-type techniques, are the most widely adopted approaches for improving soft and compressible soils due to their high compressive strength and stiffness compared to the soft soil. Depending on the type of installation, the soil surrounding column is compacted due to displacement so it will improve soil stiffness. Sand and stone column are used to reinforce weak soil, reduce the settlement and improve the ability of foundation, accelerate the consolidation rate, improve the soil carrying capacity, and as drainage for excess water pressure dissipation in subsoil under loading [١- 4]. It is common to use crushed stones or gravels as backfill materials for improvement of foundation in many countries around the world but at present time, clean well graded sands are used as alternative backfill materials. The sand columns and sand compaction piles based on similar concept to stone columns except that sand columns are compacted in the field by using vibrating a closed end pipe to the required depth [5]. As the pipe is subsequently extracted from the ground, the hole is filled with sand. In Japan, they have been utilized broadly for the support of fills, embankments, tanks, and other different structures [1]. They are implemented by driving a steel casing down to the desired elevation using a heavy, vertical

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vibratory hammer located at the top of the pile. As the pile is being driven, the casing is filled with sand. The casing is then repeatedly extracted and partially retrieves using the vibratory hammer. By the time, when the sand compaction pile has been completed, the casing is removed from the ground [1, 5]. Thus, the use of sand column rather than stone column is a good choice for its economic [6]. Field control of soil improvement achieved by sand/stone or gravel columns requires a relatively considerable experience and efforts [5].

The degree of improvement in carrying capacity and reduction in settlement of a soft soil by sand columns is due to two factors. The first one is inclusion of a stiffer sand column in the soft soil. The second factor is the compaction of well graded sand at high relative density. In recent years, many studies and attempts have been carried out to increase the stiffness of stone columns as well as sand columns by mixing additives with the backfill material or by using different patterns of encasement [7]. Good improvements in load carrying capacity of sand columns and significant reduction in settlement have been obtained by Al-Saoudi et al. (2014) [8] who used lime as an additive to increase the stiffness of sand columns.

The aim of this study is to investigate the effect of sand columns (mixed with silica fume using different percentages) on soft clayey soil and to evaluate the degree of improvement in load carrying capacity and settlement reduction ratio of sand columns.

Experimental Work

Materials Used

Soil

The soil used in this study is a remolded soil brought from Al-Nahrawan area, Baghdad, Iraq. It consists of 16 % sand, 34 % silt and 50 % clay. Atterberg´s limits revealed L.L = 37 and P.I = 16. The soil is classified as CL (clay of low plasticity) according to the Unified Soil Classification System (USCS). From direct shear test, the cohesion (c) of the soil is 35kN/m^2. Other physical properties of the soil are summarized in Table 1.

Table (1): **Physical properties of natural soft soil**

Index Property	Index Value
Liquid Limit (L.L %)	37
Plastic Limit (P.L %)	16
Shrinkage Limit (S.L %)	12
Plasticity Index (P.I %)	21
Activity (A_t)	0.81
Specific Gravity (Gs)	2.65
Gravel (G %)	0
Sand (S %)	16
Silt (M %)	34
Clay (C %)	50
Classification (USCS)	CL

Note: All tests were performed according to the ASTM (2003)[9].

Sand

The sand used as a backfill material was brought from Al-Ekhaidhir area in the southernKarbala, Iraq. The grain size distribution showed 40% gravel, 59% sand and 1% fines classified as well graded sand (SW). The physical and chemical properties of sand are shown in Table 2. The internal friction angle (ϕ) is 44^o at dry weight of 16 kN /m^3 obtained from direct shear test.

Table (2): Physical and chemical properties of sand

Index Property	Index Value
Max. Dry Unit Weight (kN/m^3)	20.8
Min. Dry Unit Weight (kN/m^3)	16.25
D_{10} (mm)	0.24
D_{30} (mm)	0.7
D_{60} (mm)	1.7
Coefficient of Uniformity (C_u)	7.13
Coefficientof Curvature (C_c)	1.19
Gravel (G %)	40
Sand (S %)	59
Fines (%)	1
Classification	SW
Specific Gravity (Gs)	2.65
Organic Material (O.M %)	0.09
Total Dissolved Salts (TDS %)	0.3

Silica Fume (SF)

The American Concrete Institute (ACI, 1987) [10] defines silica fume as a "very fine non-crystalline silica produced in electric arc furnaces as a production result of silicon element or alloys consisting silicon". Frequently, it is a grey colored powder, similar to some extent to Portland cement or some fly ashes which exhibits both pozzolanic and cementitious properties. It has been identified as a pozzolanic admixture that is significantly powerful in improving the mechanical properties. By using silica fume together with super plasticizers, it is fairly easier to get compressive strengths within the values of 100-150 MPa in laboratory [11]. The chemical and physical properties of silica fume are shown in Table 3.

Table (3): Chemical and physical properties of silica fume [10]

Chemical and physical properties	Composition
Chemical composition (%)	
SiO_2	> 85
Fe_2O_3	< 2.5
Al_2O_3	< 1
CaO	< 1
$K_2O + Na_2O$	< 3
C (free)	< 4
S	< 1
Cl^{-1}	< 0.2
L.O.I	< 6
Physical properties	
Specific gravity (G_s)	2.25

Density (gm/cm^3)	0.75
Moisture content (%)	< 2%
Specific Surface (m^2/gr)	~20

The Experimental Setup

Steel Container

The model tests were carried out by using a steel container with thickness of 4 mm and internal dimensions 600 mm × 600 mm × 500 mm.

Model footing

For all model tests, a circular steel model footing with diameter of 64.6 mm and thickness 10 mm was used.

Loading Assembly

The loading assembly consists of two main parts; a loading frame and a steel container. The loading frame consists of a steel rod with several attachments that host the loading weights. The complete assembly is accomplished to apply static vertical loads on the footing. Figure 1 shows details of the complete set-up with the main parts of the steel container and loading assembly.

Figure (1) Steel container and loading assembly

Model Preparation and Testing

Prior the stages of preparation of the soil bed, control tests were carried out to obtain a relationship between the shear strength and water content. The undrained shear strength was measured by the Vane shear device. The shear strength of soil decreases with increasing value of water content as shown in Figure 2.

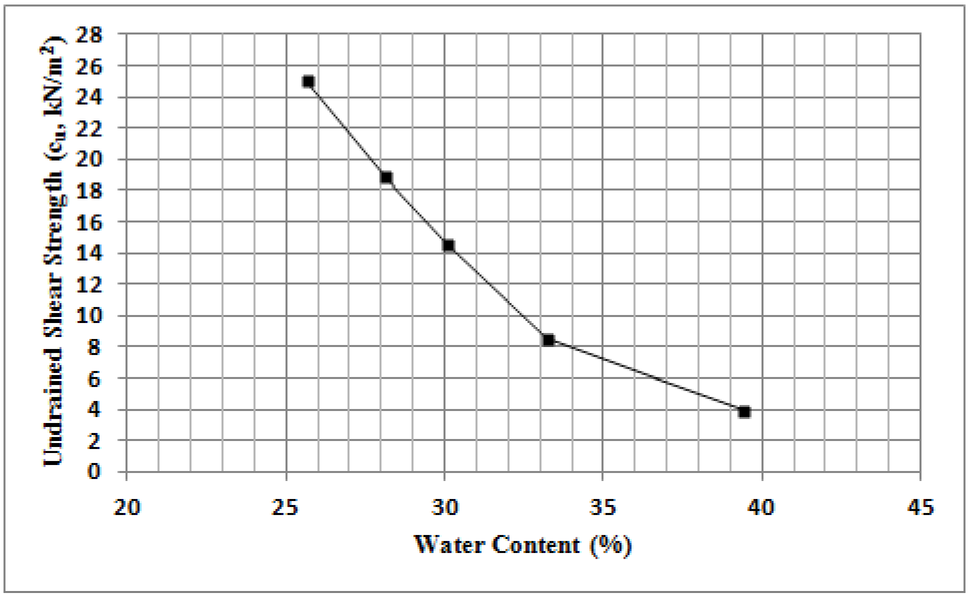

Figure (2) Variation of undrained shear strength with water content

Following this stage, the preparation of clay bed was carried out following the steps presented in Al-Gharbawi (2012) [12] and Rajab (2013) [13] as outlined below:

1. The natural soil was left for air drying and crushed by a hammer to small sizes and then crushed by using a crushing machine. The air-dried soil was divided into groups, each weighs 20 kg.
2. Each group was mixed with sufficient amount of water content within a range between 27-29%. This range of water content corresponds to undrained shear strength (c_u) between around 21–16 kN/m^2 respectively (Fig. 2).
3. After thorough mixing with water, the soil lumps were spread into the container in 5 layers until the required thickness of bed was achieved, and tamped with a special wooden tamping hammer (75 mm × 75 mm in size) to remove any entrapped air.
4. After the completion of the preparation of the soil bed, the top surface was scraped, leveled and covered with a polythenesheet and a wooden board of the same size was placed with 5 kPa seating pressure. Then, the soil layer was left for a period of two days to regain its strength by self weight consolidation.
5. The top surface of the soft soil bed was marked into four equal zones. A hole was made in the centre of each zone by gradually pushing vertically a hollow plastic pipe (PVC with external diameter of 50 mm) into the soil till the required depth of 300 mm. The soil inside the column was carefully removed from the plastic pipe by using a hand auger.

6. Later, the sand and sand-silica fume mixture were poured into the hole in layers to the full depth at dry unit weight of 17 kN/m^3 and at loose state with relative density (D_r) of 15%.
7. After the completion of the preparation of the bed of soil, a seating load of5 kN/$m^2$was placed for 24 hours. It was covered with a nylon sheet to prevent any loss of moisture and left for seven days as curing period. Following the curing days for the columns, the static loading system was placed and fixed in position and the footing was incrementally loaded with continuous measurements of settlement up to failure.

Results and Discussion

First, it is worth to mention that the failure load considered in this study corresponds to 10% settlement of the footing diameter ($D_{footing}$) and the center of the footing is coincided with the center of the column. The bearing capacity is determined using the term "bearing improvement ratio" which represents the bearing ratio (q/c_u) of the treated soil to that of the untreated soil, simply given as $(q/c_u)_t/(q/c_u)_u$. Where q represents the bearing capacity and c_u is the undrained shear strength. The settlement is determined using the term "settlement reduction ratio" which is defined as the ratio of the settlement of the treated soil to the settlement of the untreated soil and is given as S_t/S_u.

Bearing Ratio and Bearing Improvement Ratio

Untreated soil

The relationship between the applied stresses and settlement was achieved on untreated soil to be used later as a reference for different patterns of improvements. Typical results are shown in Figure 3 which relates the bearing ratio (q/c_u) versus settlement ratio ($S/D_{footing}$). Where S represents the settlement and $D_{footing}$ is the footing diameter. The bearing ratio at failure is 4.18 corresponding to 10% settlement ratio.

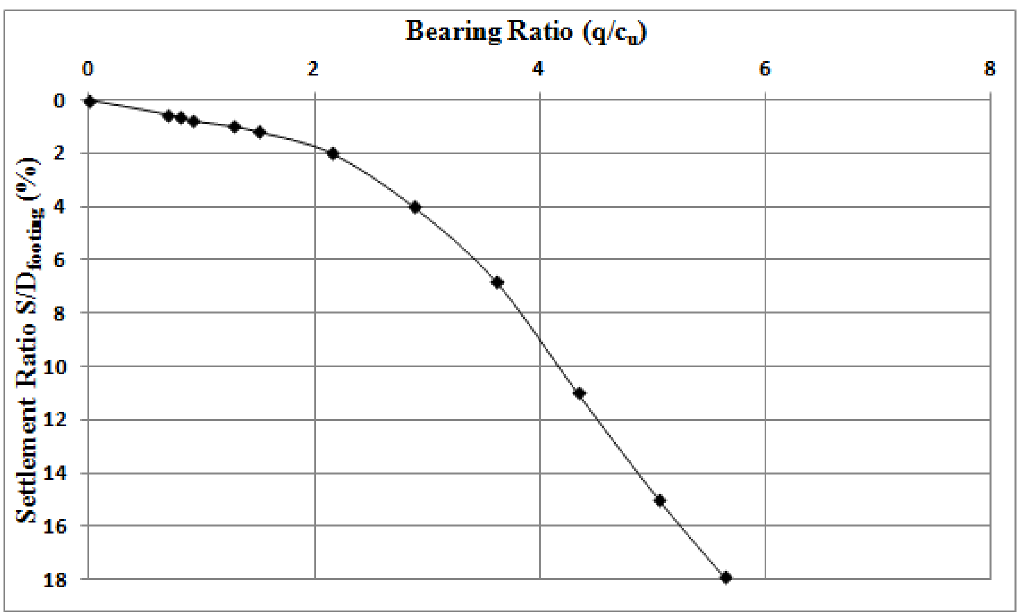

Figure (3) Bearing ratio versus settlement ratio of untreated soil

Soil Treated with Sand Columns

The relationship between bearing ratio (q/c_u) and settlement reduction ratio ($S/D_{footing}$) for soil reinforced with sand columns at a loose state with relative density of 15% is illustrated in Figure 4. From this Figure, it is obvious that at initial stress increments up to $q/c_u \approx 1$, both the untreated and treated models exhibited the same deformation reflecting no significant influence of the presence of sand columns. At this stage, no significant stress concentration was noticed and the sand columns provide no extra stiffness as compared to the surrounding soil. As the stress ratio exceeds 1.5, the bearing ratio (q/c_u) of the models starts to diverge with increasing values reaching 4.9 at failure.

The bearing improvement ratio $(q/c_u)_t/(q/c_u)_u$ versus settlement ratio ($S/D_{footing}$) shows a gradual increase in bearing improvement ratio (except the slight decrease at $S/D_{footing}$=2-3%) giving its maximum value at failure of 1.18 as shown in Figure 5. While, the variation of settlement reduction ratio (S_t/S_u) versus bearing ratio (q/c_u) shows a decrease trend in settlement ratio till q/c_u=2 then increases up to q/c_u=3 (as it has minimum bearing improvement ratio) followed again by a decrease trend with increasing bearing ratio revealing a settlement reduction ratio equal to 0.71 at failure (Fig. 6).

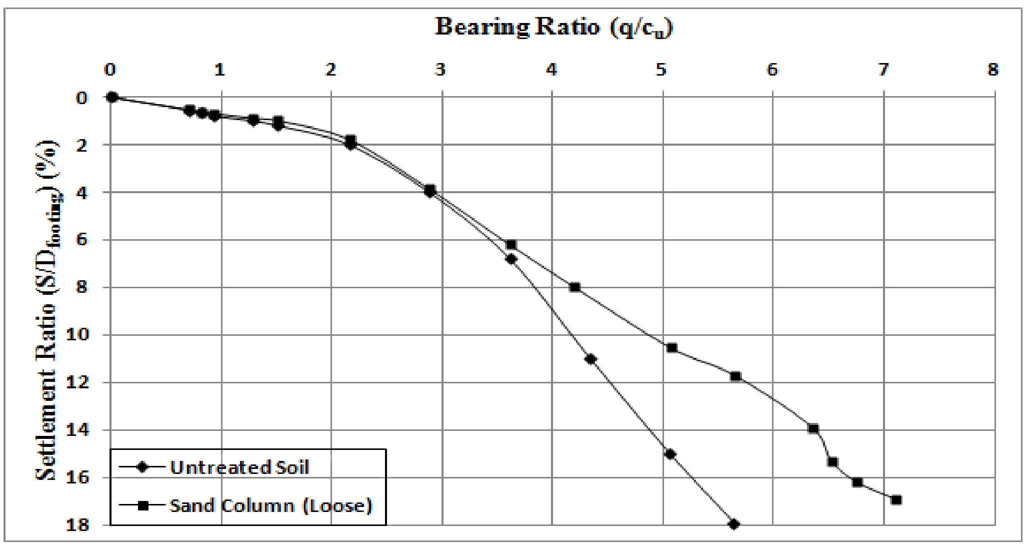

Figure (4) Bearing ratio versus settlement ratio of untreated and treated soil with sand columns

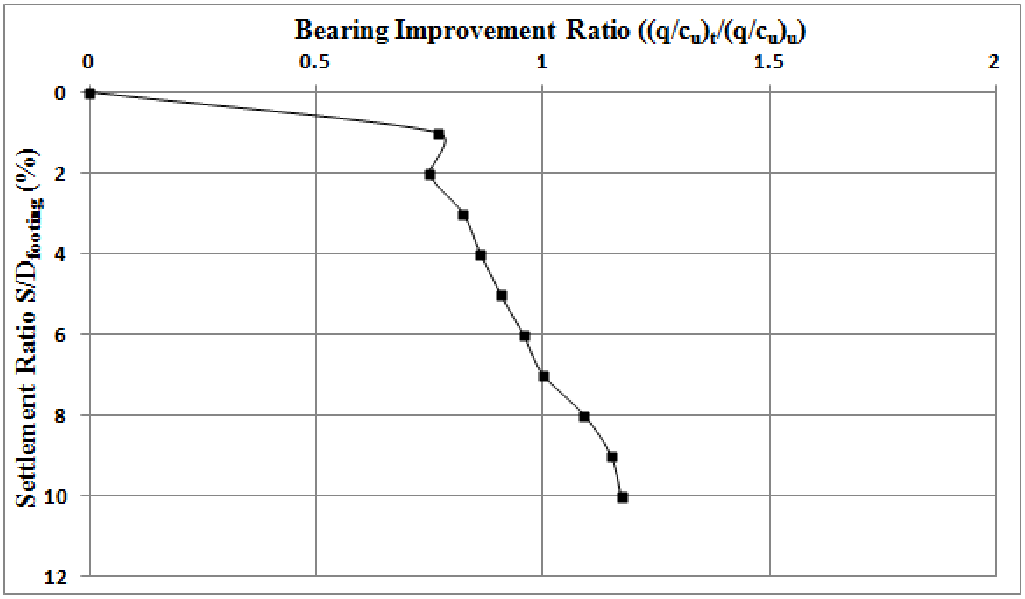

Figure (5) Bearing improvement ratio versus settlement ratio for soft soil treated with sand columns.

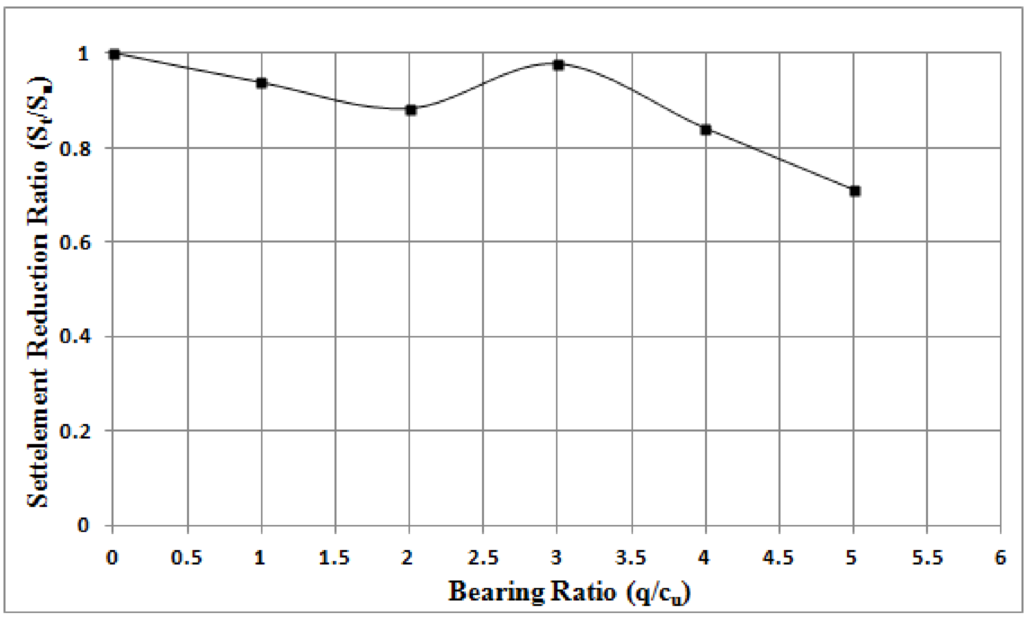

Figure (6) Settlement reduction ratio versus bearing ratio of sand columns

Soil treated with Sand–Silica Fume Columns

Three model tests were performed on sand columns stabilized with dry silica fume at loose state ((D_r= 15%), tested after 7-days curing. Figure 7 presents q/c_u versus $S/D_{footing}$ for all percentages (3, 5 and 7%) of silica fume used. At initial stress increments up to $q/c_u \approx 2$, the untreated and treated models exhibit approximately the same deformation indicating no significant influence of sand column and sand reinforced with silica fume. The bearing ratio (q/c_u) at failure ($S/D_{footing}$ =10%) are 5.45, 5.76, and 6.51 for 3, 5 and 7% silica fume respectively. The bearing improvement ratio $(q/c_u)_t/(q/c_u)_u$ versus settlement ratio $S/D_{footing}$ is presented in Figure 8. The results illustrate peak values in $(q/c_u)_t/(q/c_u)_{unt}$ at $S/D_{footing}$ =1% then gradually decreases reaching its minimum at $S/D_{footing}$ =2-3% followed again by an increase close to failure. The bearing improvement ratios $(q/c_u)_t/(q/c_u)_u$ at failure are equal 1.3, 1.47 and 1.56 for 3, 5 and 7% silica fume respectively. While, the variation of settlement reduction ratio (S_t/S_u) versus bearing ratio (q/c_u) shows in general a decrease trend in settlement ratio till q/c_u=1.5-2 then increases up to q/c_u=3 (as it has minimum bearing improvement ratio) followed again by a decrease trend with the increase in bearing ratio (Figure 9). The settlement reduction ratios (S_t /S_u) are equal to 0.60, 0.59 and 0.5 for 3, 5 and 7% respectively at q/c_u =5. It is obvious that the 7% silica fume content is found to be the best possible content with maximum bearing improvement ratio of 1.56 and minimum value of settlement reduction ratio of 0.5 as shown in Table 4 which represents a summary of test results at failure.

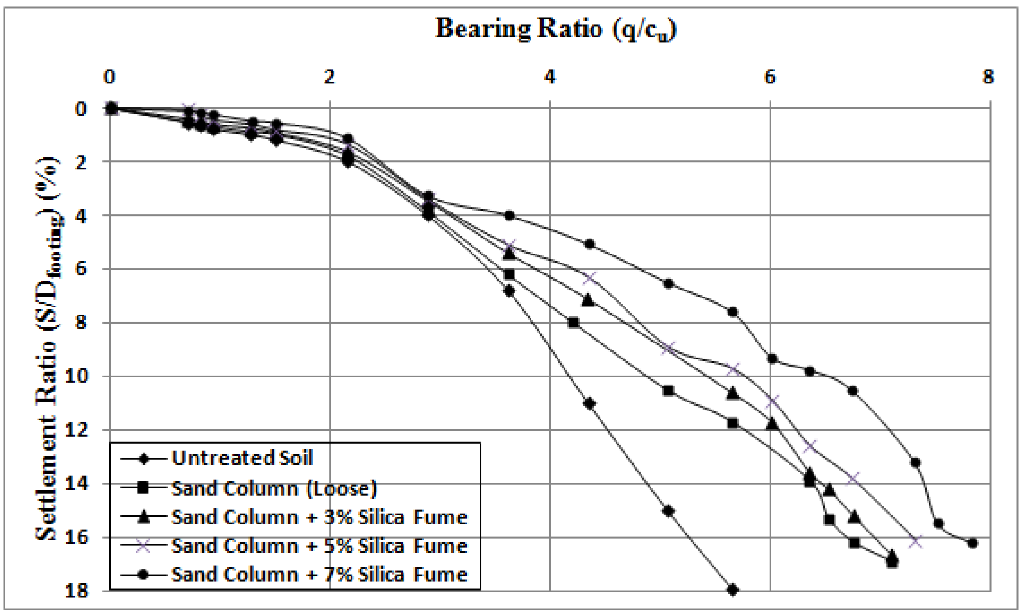

Figure (7) Bearing ratio versus settlement ratio of sand columns treated with dry silica fume.

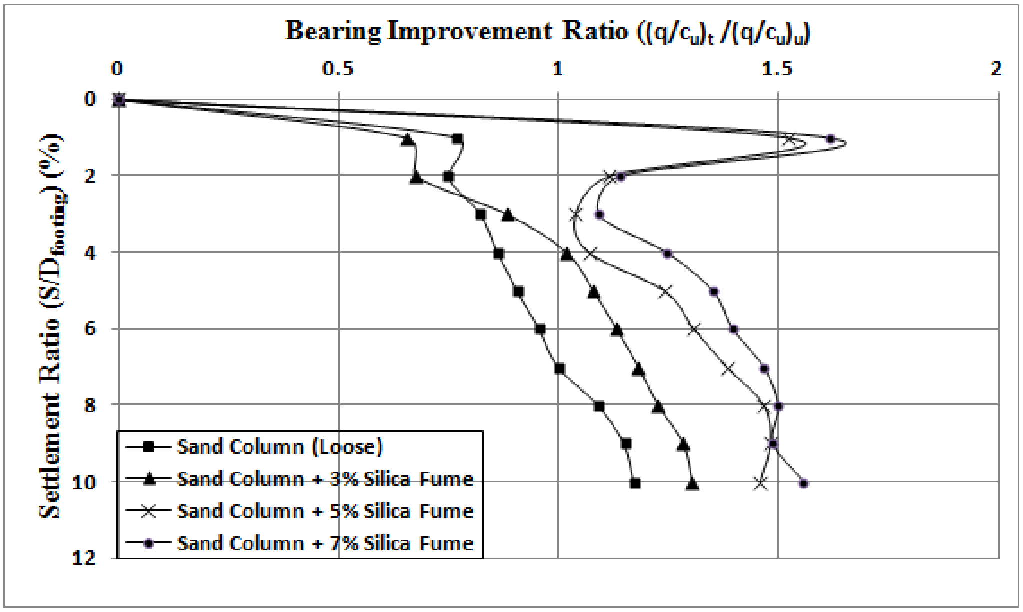

Figure (8) Bearing improvement ratio versus settlement ratio of sand column treated with dry silica fume.

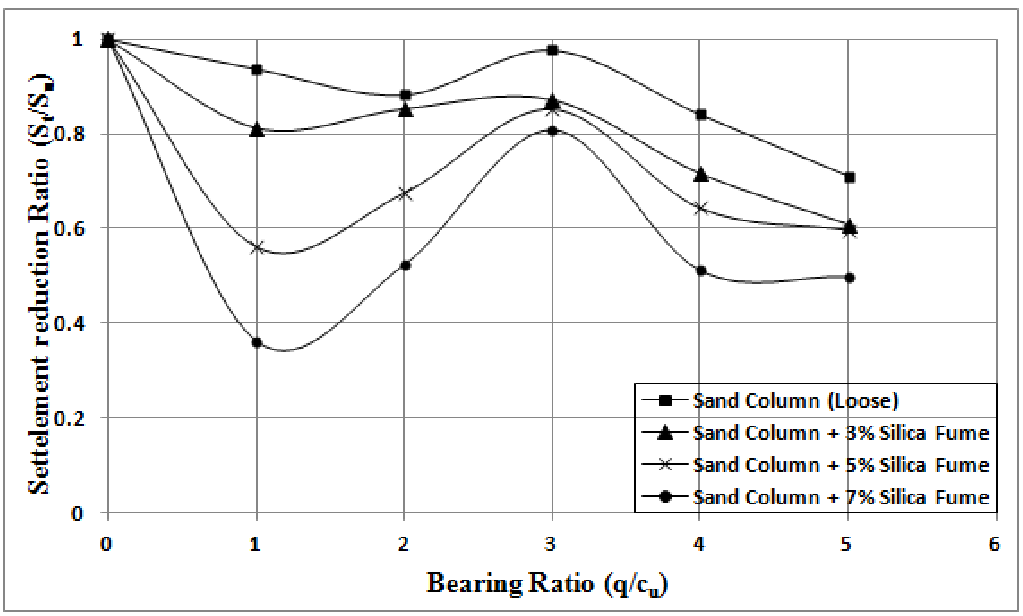

Figure (9) Settlement improvement ratio versus bearing ratio of sand column treated with dry silica fume.

Table (4)A summary of test results at failure.

Type of Soil	q/c_u	$(q/c_u)_t/(q/c_u)_u$	S_t/S_u
Untreated soil	4	-	-
Sand column only	4.9	1.18	0.71
Sand column + 3% silica fume	5.45	1.3	0.60

Sand column + 5% silica fume	5.76	1.47	0.59
Sand column + 7% silica fume	6.51	1.56	0.50

CONCLUSIONS

In the light of experimental model tests, the following conclusions can be drawn:

1. The results analysis of the model tests indicated an encouraging improvement in load carrying capacity of the columns and considerable reduction in the settlement compared to the conventional stone columns.
2. It is worth mentioning that the values obtained for bearing improvement ratio and settlement reduction ratio are limited to type the silica fume used in the tests.
3. The bearing improvement ratio and settlement reduction ratio exhibited by the sand columns are 1.18 and 0.71 respectively.
4. The best possible addition of silica fume content in sand–silica fume columns is 7%, giving bearing improvement ratio and settlement reduction ratio of 1.56 and 0.5 respectively.

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