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Assessment of Bearing Capacity and Settlement Characteristics of Organic Soil Reinforced by Dune Sand and Sodium Silicate Columns: A Numerical Study

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ABSTRACT

Organic soil is problematic soils in geotechnical engineering due to its properties, as it is characterized by high compressibility and low bearing capacity. Therefore, several geotechnical techniques tried to stabilize and improve this soil type. In this study, sodium silicate was used to stabilize sand dune columns. The best sodium silicate concentration (9%) was used, and the stabilized sand dune columns were cured for seven days. The results for this soil were extracted using a numerical analysis program (Plaxis 3D, 2020).In the case of studying the effect of (L/D) (where ''L" and ''D'' length and diameter of sand dune columns) of a single column of sand dunes stabilized with sodium silicate with a different diameter, the results showed that the best effect was for L/D of (4) with D equal to (0.7m) in the end bearing columns type. In the case of studying a group of columns, the percentage of improvement in soil bearing ratio increased with increasing the number of columns in both floating and end bearing types. When using (8-columns) with a square distribution pattern, the optimum improvement was at the end bearing and at the ratio L/D of (6), where the improvement percentage was (666%) compared to the unimproved soil.

Keywords: Organic Soil, Sand Dune, Problematic Soils, Bearing Capacity Ratio, Settlement Ratio.

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تقييم خواص قابلية التحمل والهبوط للتربة العضوية المسلحة باعمدة الرمال الكثبانية وسيليكات الصوديوم دراسة عددية

أمين محسن جاسم * , محمود ذياب أحمد

قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد, بغداد، العراق

الخلاصة

التربة العضوية من الترب ذات المشاكل في تخصص الهندسة الجيوتقنية وذالك بسبب خواصها الضعيفة حيث تمتاز بانها عالية الانضغاط وذات ضعف في قابلية التحمل لذالك كانت هناك تقنيات جيوتقنية عدة لمحاولة تثبيت وتحسين هذا النوع من التربة .في هذا البحث تم استخدام أعمدة الكثبان الرملية المثبتة بسيليكات الصوديوم حيث تم استخدام هذه الاعمدة بأبعاد مختلفة داخل هذا النوع من التربة حيث تم الحصول على أختيار أفضل نسبة من مادة سيليكات الصوديوم والتي هي (9%) وفي وقت معالجة سبعة أيام في تثبيت أعمدة الكثبان الرملية وتم اعتماد استخراج النتائج لهذه التربة بأستخدام برنامج التحليل العددي (Plaxis 3D ,2020). ففي حالة دراسة تأثير نسبة (طول/قطر) بأستخدام عمود منفرد من الكثبان الرملية مثبت بسيليكات الصوديوم وبأقطار مختلفة فقد بينت النتائج أن أفضل تأثير تم الحصول عليه عند النسبة (طول/قطر=4) وبقطر=0.7 م في حالة العمود الممتد الى النهاية الصلدة. أما في حالة أستخدام مجموعة أعمدة من الكثبان الرملية مثبتة بسيليكات الصوديوم فقد بينت النتائج عند زيادة عدد الأعمدة تزداد معها نسبة قابلية التحمل للتربة العضوية وفي كلا الحالتين الأعمدة الطافية والأعمدة الممتدة الى النهاية الصلدة حيث أن أفضل نسبة تحسين تم الحصول عليها كانت عند أستخدام (8- أعمدة) بنمط توزيع مربع و في حالة العمود الممتد الى النهاية الصلدة وفي النسبة (طول/قطر=6) حيث بلغت نسبة التحسين (666%) بالمقارنة مع التربة غير المحسنة.

الكلمات المفتاحية: تربة عضوية , كثبان رملية , تربة ذات مشاكل , نسبة قابلية التحمل , نسبة الهبوط.

1. INTRODUCTION

There are usually problems with organic soil during or after construction. This occurs due to the soil's low permeability, high compressibility, and low bearing capacity. Buildings built on this soil may experience differential settlement, leading to structural elements showing visible cracks. The improvement of organic soil was affected by many factors, such as physical, chemical, mineralogical properties, and water content **(Mitchell and Soga, 1993**; **Huat et al., 2011)**. Chemical stabilization with binders such as lime, fly ash, sodium Silicate, and cement can be frequently done at a low cost. So chemical stabilization becomes a critical alternative **(Keshawarz and Dutta, 1993; Parsons and Kneebone, 2005)**.
Thus, unique soil improvement methods are needed like chemical stabilization **(Sukmak et al., 2013; Chai et al., 2014)**, soil densification **(Disfani et al., 2014; Rashid et al., 2017)**, using a modern method (Jet grouting) that gives good results in improving bearing capacity and reducing the settlement for a wide range of soil types **(Al-Khadaar and Mahmood, 2023)** and others. **(Kareem and Jahanger, 2023)** studied evaluates the bed soil's physical,

mechanical, and chemical properties at certain southern Iraqi central marshes sites, where this region is characterized by its organic content and characteristics varying from one place to another, as the percentage of organic matter in it ranges, according to the study, from 4.5% to 9.5%. Several researchers studied the properties of the organic soil, such as **(Zbar et al., 2013),** who found that the plastic and liquid limits increased with the increase in organic content. They also noted that the maximum dry density and the optimal moisture content decrease slightly with the increase in organic content, then tend to increase. The decrease in the maximum dry density with the increase in organic content is due to a reduction in specific gravity. **(Majeed et al., 2016)** found that the cohesion value decreases with the increase in the lime for each percentage of organic content for decomposed samples. The friction angle increased with the increase in organic content for each percentage of the lime content.**(Fattah et al., 2021)** studied the organic soil in the Halfaya oil field in Amarah, where the study concentrated on the multistage oedometer relaxation test. According to the results of long-term stress relaxation, there is a linear relationship between the amount of stress relaxation and the logarithm of time after a certain amount of time.

Sand is a term used by engineers to refer to soil particles having a diameter of 0.06 mm to 2.00 mm, according to (Massachusetts Institute of Technology). Sand, conversely, is a soil particle that is too heavy to be suspended in the air but is light enough to be carried by the wind, according to geologists **(Hirmas, 2008; Bagnold, 2012)**. The dune is "a collection of loose particles, deposited or reformed by the wind, with sizes ranging from 2 mm to tens of micrometres," according to **(Mainguet, 1984),** the wind is responsible mainly for the buildup of sand. However ice and water are primarily responsible for the actual erosion of rock elements into sand grains. In Iraq, midday winds in July might reach a peak speed of 3.3 m/s on average (3.0 m/s) has been identified as the threshold velocity for soil and sediment particle movement **(Dougrameji, 1999)**. Due to this geographic basin, the air pressure is lower in the Iraqi plain and nearby high mountain ranges. Since the wind was blowing this way from all directions, the wind direction went parallel to this strip from northwest to southeast. Because of this, the strip is more susceptible to wind erosion than other parts of Iraq, making it more conducive to developing dune formations. Most of Iraq is covered with sand dunes, mainly in the central part. The alignment of the dune regions in a northwest-southeast direction is intriguing **(Al-Taie, 2002).** There are many methods used to stabilize and improve this type of soil. Sand compaction piles and stone columns represent the most improved technology that is widely used worldwide to get the improvement of bearing capacity and reduce settlement **(AlHassnawi, 2013). (Al-Hillo, 2009)** studied the behavior of a foundation supported by a dune sand column under the foundation and used dune sand to improve the behavior of soft soil. The study found that bearing capacity had significantly improved. In some (thickness of column/width of footing) ratios, it was about 892 %. There was also a decrease in settlement. Using dune sand in improvement projects is a good idea since it can be cheap. **(Al-busoda and Salman, 2013)** used geogrid and geotextile material with sand dunes to improve gypseous soils with several types of loads, and it gave good success results, as sand dunes were used interspersed with geogrid and geotextile at specific depths over gypseous soils, which increased the bearing capacity of these soils. **(Al-busoda and Salem, 2012)** studied Affek dune sand, and the result showed it has a small to moderate potential depending on the degree of stress, according to the findings of collapse tests. The reduction in ideal condition-bearing capacity due to soaking in water was around 45%. The bearing capacity of the square footing was larger than the circular and rectangular footing.

Sodium silicates are complex chemicals with unique physical and chemical properties. Adhesives, cement, cleaners, deflocculation, surface coatings, corrosion inhibitors, catalysis bases, cleaning chemicals, and washing agents are all used in the manufacturing process. Appropriate for its intended purpose, silicates are produced in different alkali-to-silica (Na_2O/SiO_2) ratios, water concentrations, and particle sizes. Silica, sodium salts, and water, all common raw materials, are used to make them. Since manufacturers have a large product distribution infrastructure, sodium silicates are easily available and may be obtained in some commercially used containers **(Hurley and Thornburn, 1971).** Silica (SiO_2) originates from sand, alkali (K_2O or Na_2O), which comes from potash or soda, and water are the three primary ingredients of all silicates **(Peter, 2003)**.
This work aims to improve the bearing capacity and reduce the settlement of organic soils by using columns composed of sand dunes and sodium silicate and to know the extent of their effect on improving this type of soil in terms of extracting the best (L/D) ratio under footing of single column, while group columns will studying effect of number of columns with different diameters and different ratio of (L/D) for floating and end bearing columns type by using the numerical analysis program (Plaxis 3D, 2020).

2. THE MATERIALS USED AND METHOD OF TESTING

2.1 Organic Soil

The soil used in the testing program was obtained from the Halfaya oil field (42 km southeast of the city of Amarah and about 420 km southeast of Baghdad city) and a depth of 1.5 m. This soil contains 4.2% organic matter that was collected and transported to the laboratory (Amarah Technical Institute Laboratory), and to achieve the requirements of the study and achieve the percentage of organic matter in the soil, this soil was mixed with organic materials by weight where several trials until reaching to the result of this mixed is 20.3% of the organic content. The basic properties of the studied soil are presented in **Table 1.**

Table 1. Properties of studied soil.

Index property	Value	Standard
Liquid limit (L.L) (%)	60.9	ASTM D-4318
Plastic limit (P.L) (%)	35.5	
Plasticity index (P.I) (%)	25.4	
Specific gravity (Gs)	2.63	ASTM D-854
Unit weight (γ)(kN/m^3)	12.2	
Shear strength (c) (kPa)	18	ASTM D-2166
Organic matter (%)	20.3	ASTM D-2974

2.2 Sand Dune

The sand dunes were brought from a site located west of Al-Amarah (73 km from the center of the city of Al-Amarah and about 390 km to the south of Baghdad), as shown in **Fig. 1.** The basic properties of dune sand are presented in **Table 2**.

Figure 1. A map and site of the sand dune of west Amarah city.

Table 2. Properties of dune sand.

Index property	Value	Standard
Max. dry unit weight (kN/m^3)	15.55	ASTM D-4253
Min. dry unit weight (kN/m^3)	13.17	ASTM D-4254
Specific gravity	2.66	ASTM D-854
Gravel (%)	0	ASTM D-422
Sand (%)	97.6	
Fine (%)	2.4	
Organic matter (%)	2.53	ASTM D-2974

2.3 Sodium Silicate

The sodium silicate material used in this practical program is liquid sodium silicate, which was brought from the scientific offices market in Baghdad, where the technical characteristics of this material are as in **Table 3**.

Table 3. Properties of sodium silicate.

Index property	Value
Density -20 Baum	51±0.5
Specific gravity	1.543
Viscosity (CPS) (at 20 °C)	900
Na_2O %	13.4
SiO_2 %	32.5
Appearance	Colorless liquid
pH (at 20 °C)	11.75

2.4 Selecting the Best Proportion for Mixing of Sodium Silicate and Dunes Sand

- Mixing sodium silicate with dunes sand was carried out according to the following ratios [5, 7, 9, and 11 %] as a percentage of sodium silicate.
- The unconfined compressive strength test was also carried out for all proportions of the mixture using an (unconfined compressive test) according to the specification (ASTM-D2166) and with different curing times (3, 5, 7, and 14) days. A mold with a height of 9 cm and a diameter of 4 cm was used. The mold dimensions must be satisfied (L/D = 2 to 2.5) according to (ASTM-D2166). After that, sand was placed inside the mold in three layers. Each layer is hammered to achieve the required density. After that, the samples were preserved for curing before being tested by covering them with nylon sheets**.**
- The effect of adding sodium silicate to the sand is an improvement in the properties of the dune sand. The unconfined compressive strength of the sand after (3, 5, 7, and 14) days of curing time was well improved, and the models began to harden after a few hours of mixing. Good improvement was observed at 9% of sodium silicate, as this indicates that sodium silicate improves the geotechnical properties of the models to certain proportions and vice versa. The effect is negative at high percentages at 11%, where the cohesion strength decreases because the percentage of sodium silicate increases as sodium silicate becomes a lubricate rather than a cementing agent.
- The highest cohesion strength was obtained by adding (9%) sodium silicate at the time of treatment (14) days. When the curing time increases, the cohesion strength also increases. Because of the convergence of the results of cohesion strength between (7) and (14) days, (7) days were chosen as a good time for processing to improve the geotechnical properties of the dune sand models. **Fig. 2** shows the method testing, and **Fig. 3** shows the results summary.

Figure 2. The Dune Sand column specimen stabilized with sodium silicate during the testing.

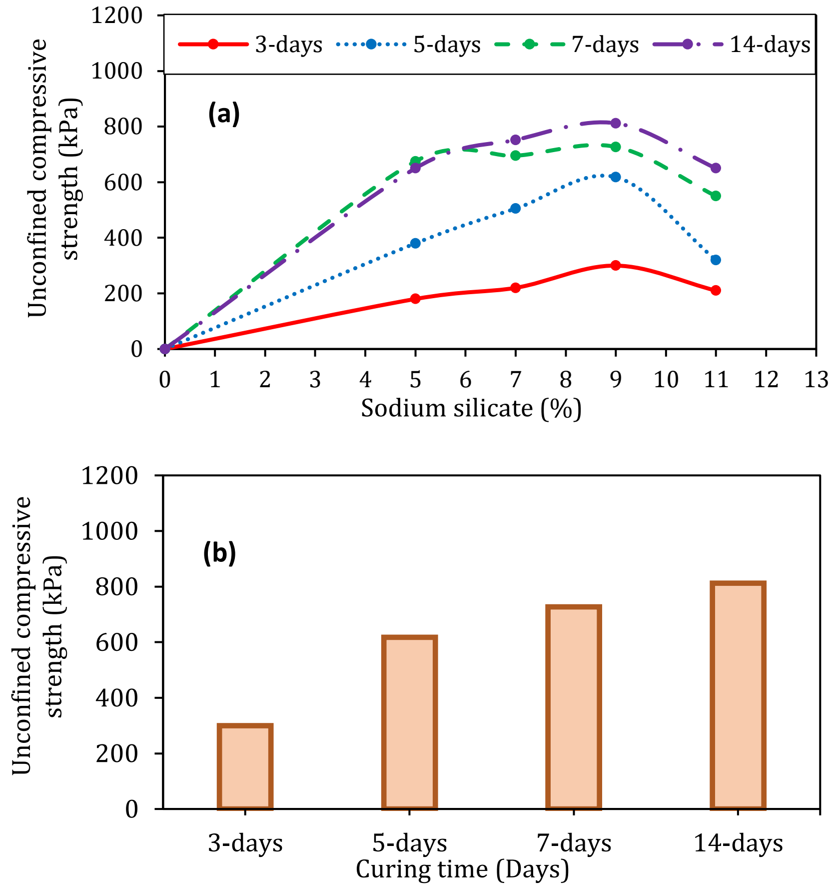

Figure 3. (a) Effect of sodium silicate content and (b) Effect of curing time on unconfined compressive strength of dune sand column.

3. FINITE ELEMENT METHOD

3.1 Experimental Work for Verification

A comparison of experimental and numerical data has been carried out to validate the numerical model with the experimental work.
This verification used the model box's interior dimensions from experimental laboratory testing to simulate equivalent boundary situations. The model's dimensions, determined by a single borehole at its initial corner, were 0.6 m x 0.6 m x 0.6 m. The points in the model that include information on the soil profile may be called boreholes. Due to the model's lack of consideration for the water conditions, the hydraulic head was below the soil profile. A stiff surface plate square footing measuring (0.1 m X 0.1 m) was used to carry the weight. Two case studies were used to confirm the findings. The first case is for untreated organic soil. The results of a group and column stabilized with 9% sodium silicate (end-bearing type) are presented in the second case. According to **Figs. 4 and 5,** the study demonstrates close qualitative behavior between experimental data and finite element results especially before 10mm of the settlement.

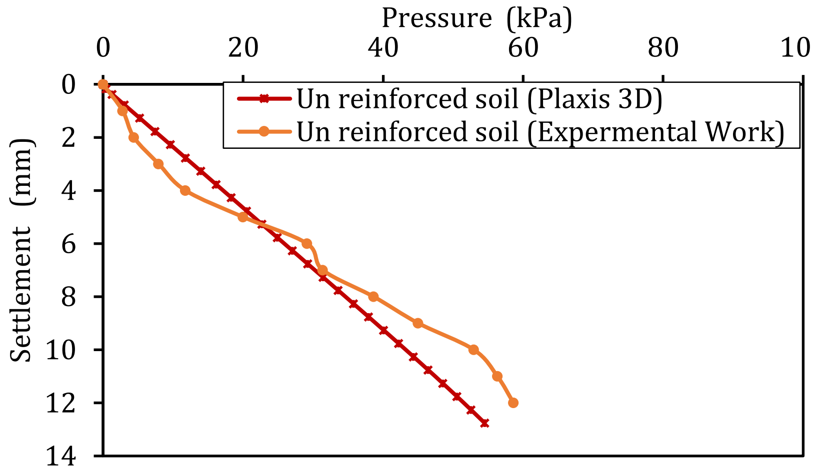

Figure 4. Bearing pressure-settlement relationships for unreinforced soil.

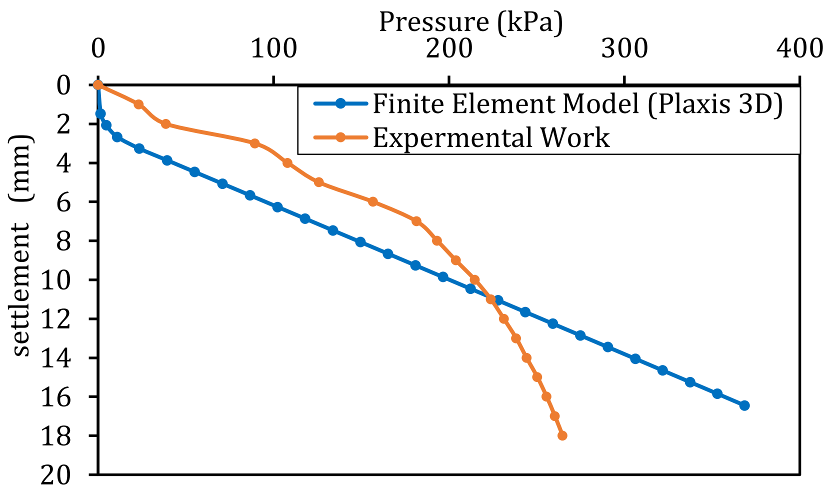

Figure 5. Load-settlement relationships for dune sand columns stabilized with 9% sodium silicate (end-bearing type).

3.2 The Parameters Used in the Study

The characteristics of the soil studied and dune sand columns that stabilized with (9%) sodium silicate for the analysis of a numerical method are represented in **Table 4.** The **Table 5.** represents the parameters for the concrete footing that is used in this study.

3.3 Analysis of a Footing Resting on Untreated Organic Soil

According to **(Lautenegger and Adams, 1998),** the most straightforward method for determining ultimate bearing capacity is the load settlement relationship. The finite element mesh and nodes are shown in **Fig. 6.** To directly normalize the pressure and settlement ratio (S/B), where (S: Settlement and B: Footing width) a unit area footing (1 m x 1 m) is used. The PLAXIS 3D-analyzed footing's (q/c) (where q is the applied stress, and c is the shear strength of organic soil) against ($S/B_{footing}$) is shown in **Fig. 7.**

Table 4. Properties of studied soil and dune sand columns.

The properties	The materials		Standards
	Dune sand stabilized with sodium Silicate	Studied soil	
Material Model	Mohr-Coulomb	Mohr-Coulomb	
Unit weight (γ) (kN/m^3)	15.6	12.2	
Modulus of elasticity(E) (kPa)	14000	5200	ASTM D-2850
Poisson's ratio (v)	0.3	0.35	
Angle of internal friction (ϕ)(deg.)	41	19	(ϕ=41)ASTM D-3080 (ϕ=19) ASTM D-2850
Dilatancy angle (Ψ))(deg.)	11	0	
shear strength (c) (kPa)	726.79	18	ASTM D-2166

Table 5. Properties of footing **(PLAXIS Edition and Manual, 2021**).

Parameter	Value
Material model	Liner elastic
Material type	concrete
Drainage type	Non–porous
Unit weight (γ)(kN/m^3)	24
Young modulus (E) (kPa)	2.6x10^7
Poisson's ratio (v)	0.2

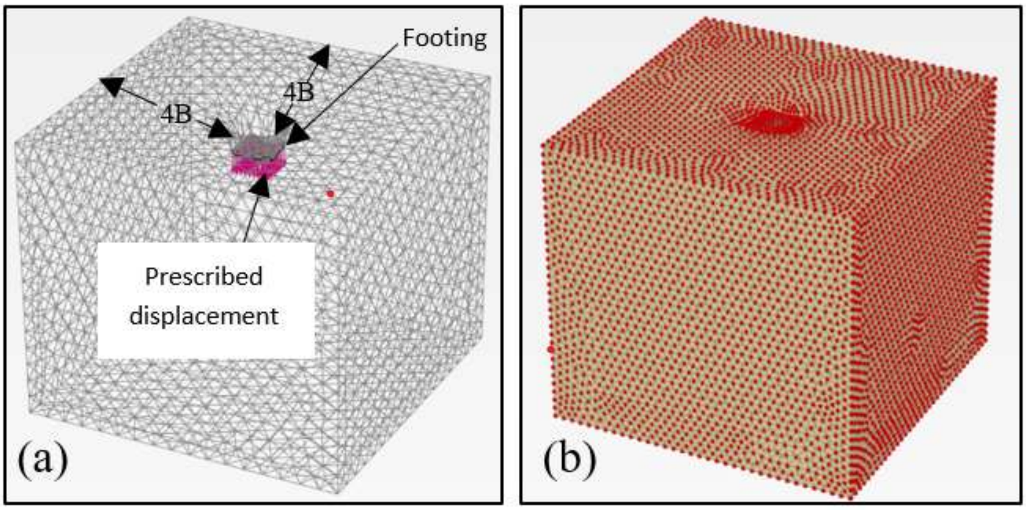

Figure 6. (a) The numerical soil model, and (b) the mesh and nodes for the finite element.

The unimproved soil's ultimate bearing capacity, calculated from the load settlement curve and specified using the (0.1B) method, is (29) kPa. This method (0.1B) is according to **(Terzaghi, 1947),** where the failure is the load equivalent to (10%) of the width of the foundation or diameter of the pile.

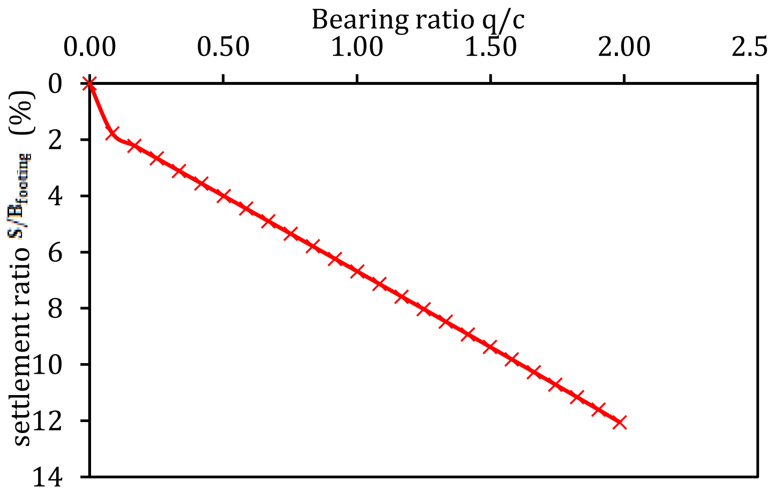

Figure 7. The settlement ratio ($S/B_{footing}$) versus the bearing ratio (q/c) for the untreated organic soil.

3.4 The Effect of (L/D) on Single Column Analysis Results

To evaluate the behavior of a single column under an axial load, 12 models have been studied. This section involves how the length/column diameter ratio (L/D) affects the modeling results. Three values for floating and end-bearing types (L/D = 4, 6, and 8) and two diameters (0.5 m and 0.7 m) are investigated.
The (q/c) versus ($S/B_{footing}$) for single columns resting on an isolated footing for (0.5m and 0.7m) diameter in the floating type shown in **Fig. 8**.

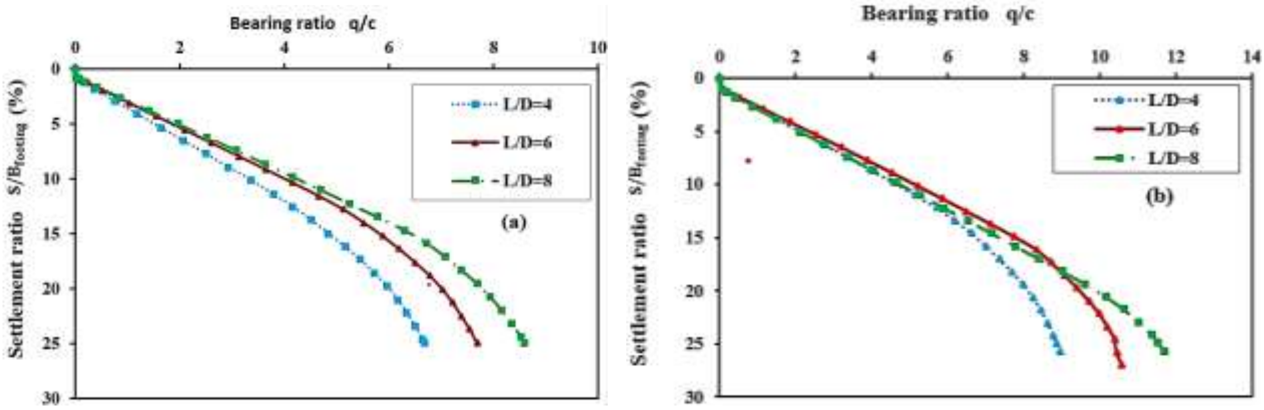

Figure 8. The bearing ratio versus the settlement ratio for a single floating column for: a) D = 0.5, b) D=0.7.

From the figure, it is noted that the best result was obtained for the bearing ratio, which amounted to (q/c =4.16) when the settlement ratio was 10% of the foundation width. It was when using the ratio (L/D = 8) and at (D= 0.5), but when the diameter was increased to (D= 0.7), the best result was at the ratio (L/D = 6), where the bearing ratio increased to

(q/c =5.2), and this increase may be due to the increase in length and diameter, which negatively affects the improvement process of floating columns type.
The (q/c) versus (S/$B_{footing}$) for single columns resting on an isolated footing for (0.5m and 0.7m) diameters; in the end bearing type shown in **Fig. 9,** from the curves, where the best result of the bearing ratio was obtained at the ratio (L/D= 4) and in both cases when using (D= 0.5 and 0.7), but the diameter that gave the best results was (D= 0.7), with a bearing ratio of (q/c =12.94), and the reason for the improvement is less when using (L/D=6 and L/D=8). This may be because bulging failure is common in end-bearing stone columns on a hard stratum overlying organic soil **(Barksdale and Bachus, 1983).**

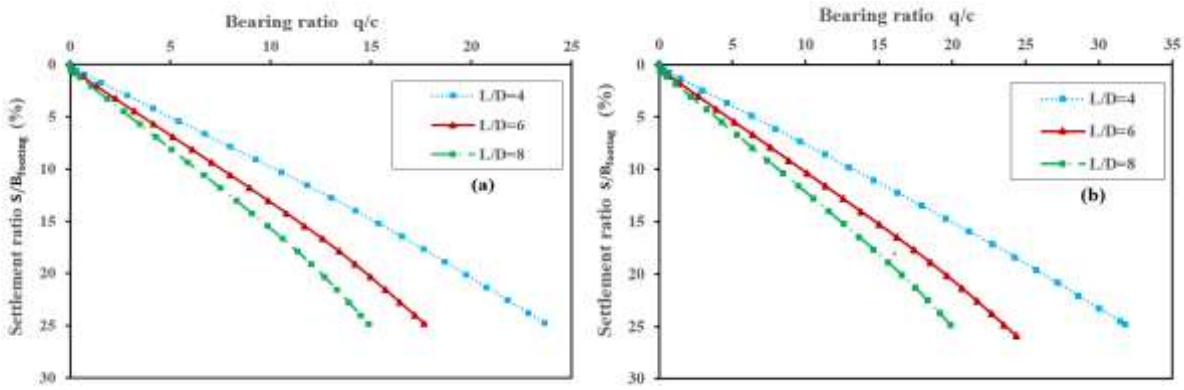

Figure 9. The bearing ratio versus the settlement ratio for a single end-bearing column type when: a) D = 0.5, b) D=0.7.

The results of the single-column study for (0.5 and 0.7m) diameters for floating and end-bearing types are summarized in **Table 6.** Through the results, we notice that the best-obtained value for the bearing capacity was when using the ratio (L/D = 4) and in (D = 0.7) and in the case of the end-bearing columns, which reached (234 kPa).

3.5 Analysis of the Group of Dune Sand Columns under the Raft Foundation

3.5.1 Boundary Conditions and Finite Element Modeling

The effect of the number of columns stabilized with 9% sodium silicate (4, 6, and 8 columns) supporting a rectangle raft foundation (4 m x 2 m) is presented. The raft size has been selected to give the group the most incredible amount of space (S = 2D) with D=0.5m. The numerical soil model for group columns is shown in **Fig. 10.** For each step, the area replacement ratio (ar.) is:

- Four regular sand columns are arranged in a square pattern with a central ar. = 0.098.
- Six regular sand columns arranged in a square pattern have ar. = 0.147.
- Eight regular sand columns arranged in a square pattern have ar. = 0.196.

Table 6. Summary of the analysis results of single columns for floating and end bearing type.

Cases	Diameter(m)	L/D	Carrying capacity (kPa)
Unreinforced	-	-	29
Floating	0.5	4	59
Floating	0.5	6	72
Floating	0.5	8	76
Floating	0.7	4	85
Floating	0.7	6	93
Floating	0.7	8	85
E.bearing	0.5	4	185
E.bearing	0.5	6	135
E.bearing	0.5	8	112
E.bearing	0.7	4	234
E.bearing	0.7	6	176
E.bearing	0.7	8	148

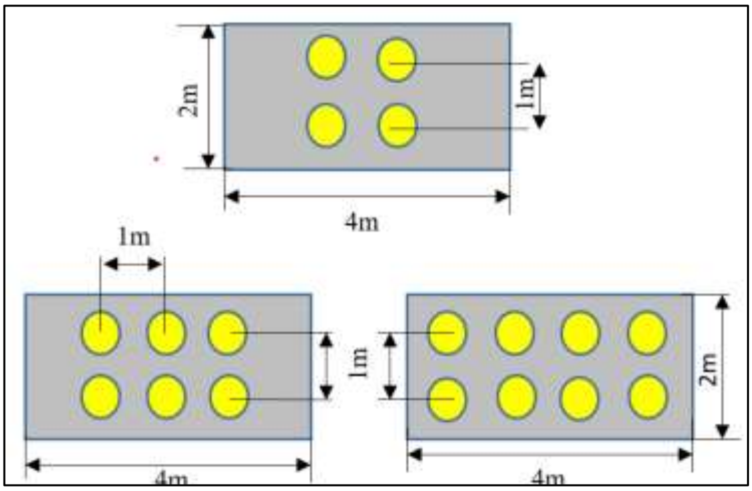

Figure 10. A numerical of dune sand columns with different layouts.

3.5.2 Columns Group under Raft Foundation Analysis Results

Fig. 11 shows the results of the comparison between the (q/c)and (S/$B_{footing}$) of the columns group (L/D = 6) and (S = 2D) for floating type, during the curve, we notice that increasing the number of columns leads to an increase in the bearing ratio until it reaches (q/c =2.04) at a settlement ratio of (10%) of the used foundation width.
Fig. 12 gives the (q/c)versus (S/$B_{footing}$) of column groups (L/D = 6) and (S = 2D) for end bearing types. During the curve, we notice that increasing the number of columns leads to an increase in the bearing ratio until it reaches (q/c =12.46) at a settlement ratio (10%) of the used foundation width, and this increased due to the organic soil being denser at certain proportions.
Figs. 13 and 14 show that for the floating and end bearing types, respectively, the (q/c)versus (S/$B_{footing}$) of column groups (L/D = 8) and (S = 2D). The results show that as the area replacement ratio rises, the confinement stress of nearby organic soil rises. The

stress concentration on the sand columns rises with the number of columns since they are stiffer than the surrounding organic soil due to the 9% sodium silicate stabilization. The foundation may settle uniformly, and the contact pressure may be redistributed due to the stress distribution under a stiff footing.

Table 7. shows that the best improvement value for the organic soil was obtained in a group of columns distributed in a square layout with the number of columns (8 columns) and with a ratio (L/D= 6) in case of end-bearing columns, Where the improvement ratio for the improved organic soil in compression with un improved organic soil is (666%).

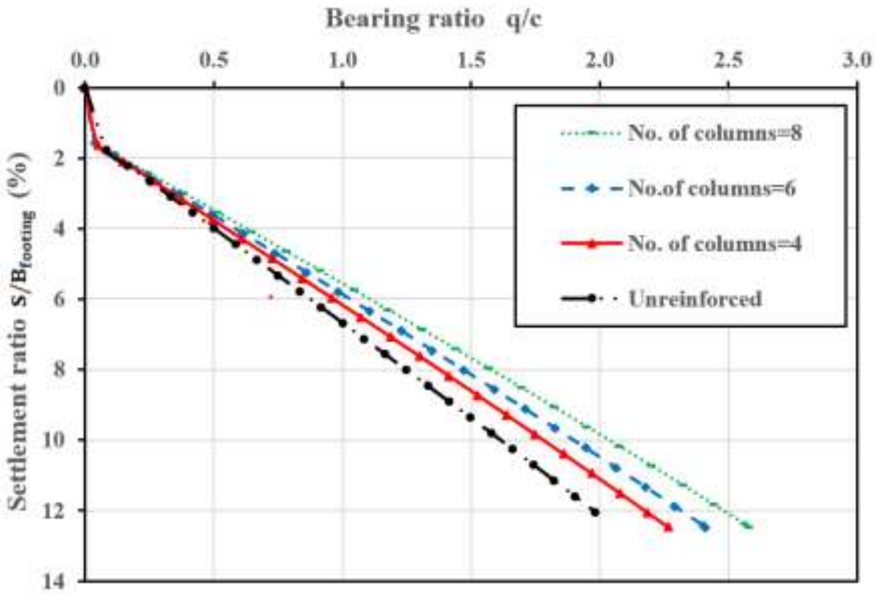

Figure 11. Bearing ratio versus settlement ratio of groups of columns in a floating type, when L/D = 6 and S = 2D.

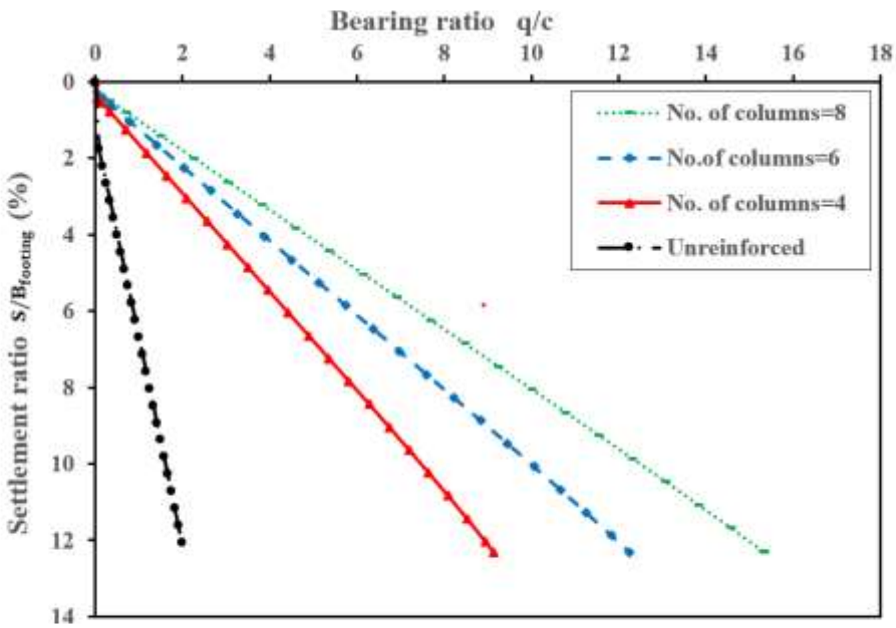

Figure 12. Bearing ratio versus settlement ratio of groups of columns in end-bearing type when L/D = 6 and S = 2D.

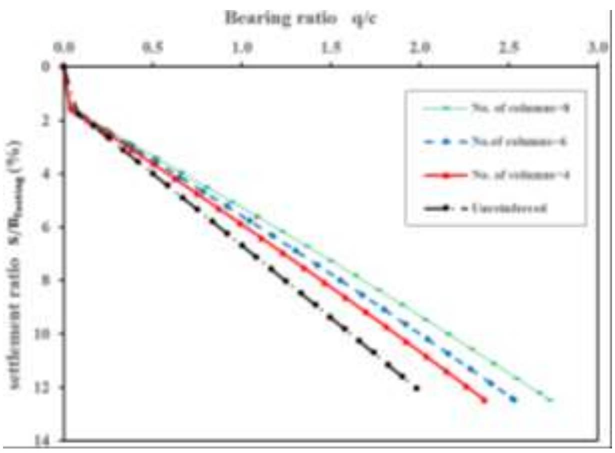

Figure 13. Bearing ratio versus settlement ratio of groups of columns in floating columns type, when L/D = 8 and S =2D.

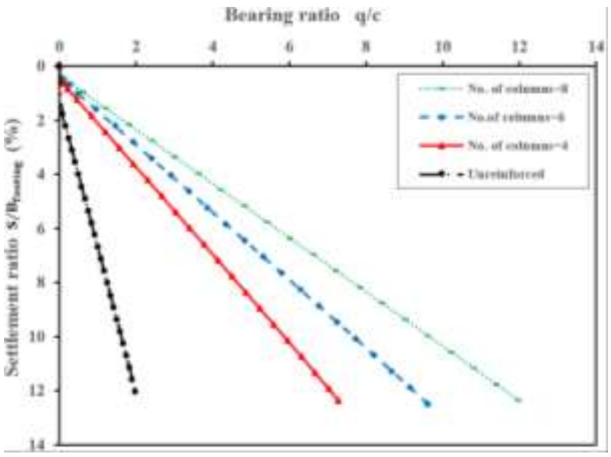

Figure 14. Bearing ratio versus settlement ratio of groups of columns in E.bearing type, when L/D = 8 and S =2D.

Table 7. Summary results of the analysis of the columns group.

Type of columns	L\D	Number of columns	Carrying capacity (kPa)	The relative improvement ratio to un-improved soil
Floating	6	4	33	14
Floating	6	6	35	21
Floating	6	8	37	28
E-bearing	6	4	137	372
E-bearing	6	6	181	524
E-bearing	6	8	222	666
Floating	8	4	33	14
Floating	8	6	36	24
Floating	8	8	39	34
E-bearing	8	4	107	269
E-bearing	8	6	139	379
E-bearing	8	8	174	500

4. CONCLUSIONS

This work is involved with enhancing the bearing capacity and decreasing the settlement of organic soils by using columns composed of sand dunes and sodium silicate. Plaxis 3D, 2020 software is used to define the effect of number of columns with different diameters and different ratio of (L/D) for floating and end-bearing column types. Based on the discussed results, the extracted conclusions can be summarized as follows:

1. Dune sand reacting with sodium silicate caused the samples to harden after a few hours. The best value of the cohesion strength for the dune sand can be obtained by adding (9%) sodium silicate.
2. The cohesion of dune sand increases when there is an increase in sodium silicate until reaching (11%), where the cohesion strength decreases because the percentage of sodium silicate increases, as sodium silicate becomes a lubricate rather than a cementing agent.

3. In the case of studying the effect of (L/D), the results showed that when using the diameters (D = 0.5 and D = 0.7), the best result was obtained in the case of floating type and when (L/D = 8); on the other hand, in the case of end bearing, it was the best result when (L/D = 4).
4. In the case of studying a group of several dune sand columns stabilized by using 9 % sodium silicate, the percentage of improvement in soil bearing ratio increased with increasing the number of columns in both floating and end bearing types.

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