scientific reports

OPEN

Bearing capacity improvement of medium clay soil using sodium silicate sand columns

Zuhair Kadhim Jahanger[1]✉, Ali J. Nouri Al-Barazanchi[2], Evan E. Al-Khalidi[3] & Azad Abbas Ahmed[4]

There is an increasing demand for multi-story buildings in Baghdad, Iraq due to the scarcity of construction space. However, most of these buildings are in the range of nine levels and are to be built on the top subsoil of a clayey layer of about 6–12 m in depth. The research aims to study the effect of end bearing and floating sand columns on medium clay and dense sandy soil as well as the mechanical strength, such as bearing capacity of the soil and settlement of the foundation. The sodium silicate end bearing and floating sand columns of different lengths to diameter (L/D) were simulated by the Mohr-Coulomb (MC) material model using a finite element method adopted by Plaxis 3D. It was shown that using sodium silicate floating sand columns on medium clay has not considerably improved the bearing capacity. However, the end bearing type can significantly enhance the bearing capacity of medium clay soil. The bearing capacity of dense sand soil decreases with an increase in L/D of more than 15. This work could be extended to analyse other soil profiles that are helpful to the future of designing foundation systems of multistory buildings on medium silty clay soil. Furthermore, future work is required to understand the deformation fields and failure mechanisms of the sand column.

Keywords Bearing capacity, Clay, Raft foundation, Sand column, Sodium silicate

Fast construction and cost-effective alternatives are always recommended to improve the properties of the soil to increase its ability in bearing the different applied stresses and to control the expected generated settlements, such as soil replacement and stone and sand column methods. In general, the subsoil strata encountered in the western part of the City of Baghdad in Iraq are a medium silty clay layer overlying medium dense to dense fine-grained clayey silty sand. It was found that both raft and pile foundations are possible alternatives for the structural foundation for the multistory structures based on the pressure imposed by the building on the underlying soil. The use of sand column probes improves the bearing capacity of soft and weak clay soil and decreases the settlement of the foundation. It seems that the soil replacement would require significant excavation if the groundwater level is likely shallow. The stone and/or sand columns are always adopted to improve the bearing capacity of the weak soil layer, i.e. on soft clay, alluvial deposits, and compressible layer and fill (i.e.[1,2]). However, improved types of sand columns can be used to enhance the bearing capacity for a wide range of soil consistency and bearing capacity[3]. They have studied experimentally and numerically the behavior of the treated dune sand columns stabilized with 8% sodium silicate for both floating and end bearing types, at the obtained results of the finite element method using PLAXIS 2D validated using the small-scale model experimental results. Optimal ratios vary, but most effective ranges fall between 8% and 12% sodium silicate by weight of sand. Emad et al.[3] and other studies suggest that exceeding 15% sodium silicate can lead to over-lubrication of sand grains. The soil bearing capacity using improved sand columns was checked using various methods, for example, experimentally using a laboratory model[4–8] and theoretically using the finite element method (FEM)[3,9,10].

Treated sand columns significantly improve bearing capacity and notable decrease in the settlement of the soil. End-bearing columns outperform floating ones in both strength and deformation control, as demonstrated in numerical studies by Al-Khalidi[3] and confirmed by experimental data from similar works[7]. Soil strength is primarily enhanced using chemical gelation of Sodium silicate, forming calcium-silicate-hydrate (C-S-H) bonds

[1]Department of Water Resources Engineering, University of Baghdad, Baghdad, Iraq. [2]Highway Engineering Department, Erbil Technical College, Erbil Polytechnic University, Erbil, Iraq. [3]College of Technical Engineering, Al-Farahidi University, Baghdad, Iraq. [4]Andrea Engineering Tests Laboratory, Baghdad, Iraq. ✉email: zk_jahanger@coeng.uobaghdad.edu.iq

among sand grains. As a result, cohesion, friction, and permeability were positively enhanced, leading to better stiffness of the sand column. Such findings were approved (i.e.[3,6,7]).

Numerous new buildings, such as multistory residential and business buildings, are expected to be constructed in the Western part of Baghdad, Iraq, with a layered soil profile of different strengths[11,12], as there is an increasing demand for flats. In general, most of these multistory building consists of 7–9 levels, in addition to a single or double-layer basement due to the demands of the scarcity of construction spaces. However, the ultimate applied load per level from such a superstructure with a reinforced concrete frame can be estimated roughly at 17–20 kN/m^2[13]. These typical maximum loads are usually related to the use of the building to which they are applied and the structural design[13]. Therefore, the total load transmitted to the raft foundation equals 140–180 kN/m^2. However, for such multistory residential and business buildings, there are no possible alternatives to using a raft foundation.

The raft foundation with enough rigidity placed at various depths below natural ground level (NGL) cast on a well-compacted sub-base layer having a thickness of at least 0.5 m varies widely from one location to another and was evaluated to be on average of 75 kN/m^2. Further, the depth of embedment is located on a clayey soil layer where most of the ground is sedimentary, medium cohesive soils strengthen with depth overlying a medium dense sand stratum[14–17]. The clay soil layer extends up to a depth of about 6–12 m[15]. The allowable bearing capacity is the minimum value determined using the well-known Terzaghi equation and the unconfined compressive strength test on samples extracted from undisturbed samples. This calculation provided that the total and differential settlement remains within the permissible limits, depending on the structure type and purpose of use. Therefore, if the raft foundation is selected to avoid costly pile foundations, the contact pressure from the superstructure will be high in magnitude. For most such cases, the loads will have to be carried through the top layer utilising piles. In such cases regarding the soil profile of the City of Baghdad, it is better to improve the properties of the topsoil to increase the allowable bearing capacity of the soil and decrease the settlement of the foundation as an economical substitution instead of pile foundations. It seems that the treatment of the topsoil layer is an alternative to enhance the bearing capacity by at least twofold, such as stone and sand columns. Hence, it seems that the soil replacement (i.e. 1.5 m) can enhance the bearing capacity by not more than about 10%, as the load can be spread on a greater subsoil area using the 2:1 method [i.e. 1, 2], the load, therefore, is lowered.

Soil mechanics is the basis of foundation design, which is necessary to study the engineering properties of subsoil and stress distribution subsoil regarding the load from the superstructure. Numerous researchers have studied the behaviour of sand (stone) columns using experiments[3,6,10], theoretical approaches[4,5], and computer simulations[6–11]. For example, the economic improvement of a structure constructed on a soft clay layer using sand columns is a practical method to increase the shear strength of the soil, reduce the settlement of the foundation, and increase the rate of consolidation of the soil. Although the use of sand columns for soil improvement is well-established, this study specifically targets medium clay soils, which are often overlooked compared to soft clays or loose sands. The chemical treatment of sand columns using sodium silicate in these soil types is still underexplored. Recent studies[3,6,7] have shown that sodium silicate significantly improves sand mechanical properties such as compressive strength and stiffness, supporting the relevance and novelty of this approach in providing practical design recommendations. It is worth mentioning that using an alternative method as sustainable construction beyond the current issue to enrich the literature is applicable and will enrich the geotechnical society[18,19].

Detailed information is still scarce in the literature on how sodium silicate sand columns are linked to the bearing capacity of medium clay and medium dense to dense sand soil, and the effects of types of sodium silicate sand columns on them for key cases such as floating and end-bearing sand columns. However, very little information is available in the literature for performing an analysis of the bearing capacity failure and deformation properties of raft foundation, sodium silicate sand column, clay and sand interactions. Two different cases of sodium silicate sand column were adapted here, for both floating and end bearing types, using FEM, which was performed using Plaxis software. The former, sodium silicate sand columns, are entirely embedded in a relatively uniform medium of silty clay soil so that shaft resistance is dominant. The latter is a sodium silicate sand column with tips embedded in a dense sand layer where most of the sodium silicate sand column's load capacity is mobilised. The limitations are considered constraints on the medium silty clay layer of low plasticity and shallow water table, and treated with sand columns mixed with 8 per cent sodium silicate. Therefore, the present work consists of theoretically evaluating the improvement of a multistory building foundation system under static loading embedded in either a uniform or layered ground of medium soil and dense sand soil structures.

Soil exploration

Field work

The drilling machines used for the fieldwork are the multi-drill method, using a continuous auger drill and the rotary drilling method using a wash drill. The wash boring method uses the rotation of the drilling bit, with continuous water pressure, to advance the borehole. The water is then forced under pressure through the hollow of the drill rod, and it emerges at high velocity through openings in the drilling bit, carrying out the fluid with eroded soil, and the fluid rises through the annular space between the drill rod and the side of the soil[20,21]. A drilling depth of 20 m was decided to penetrate relatively incompressible material beyond the influence of the foundation pressure zone, in which bulk, undisturbed, and disturbed samples were taken in 2 m intervals.

Disturbed samples using standard split-spoon samplers test (SPT) and undisturbed samples using thin wall tube samplers (Shelby Tube) were obtained and specified to determine the classification of the soil layers. It is worth mentioning that corrections have been considered for the SPT value; the correction factors for SPT are hammer release, rod length and borehole diameter. The typical soil profiles encountered at the studied locations are detailed on the borehole logs. This is a general overview of the soil profile. Figure 1 shows the locations of the

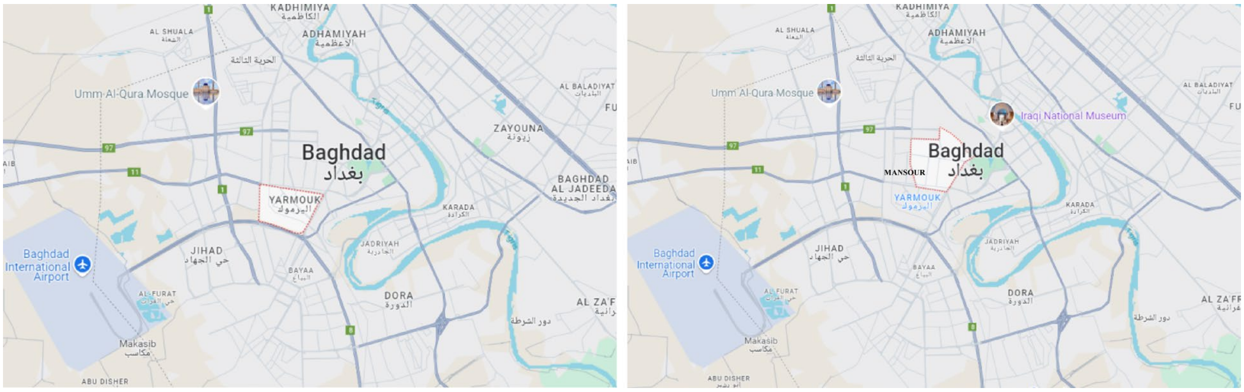

Fig. 1. Location for Western Baghdad, (left) Yarmouk Area 1 and (right) Mansour Area 2[22].

two studied areas in the City of Baghdad in Iraq. Yarmouk district is defined hereafter as area 1, and Mansour district as area 2. This was generated using the Google Earth map[22].

Description of the soil profile

The soil profiles of the proposed 8 different sites for multi-story residential buildings, which are intended to be constructed in the western districts of Baghdad Governorate, Republic of Iraq, were adopted in this study. The cohesion (c) and internal friction angle (ϕ) were obtained through consolidated undrained triaxial tests[23]. The liquid limit and plastic limit of clay were determined using Atterberg limits tests[24]. compression index (Cc), rebound index (Cr), pre-consolidation pressure (σc') and coefficient of consolidation (c_v) were measured using the consolidation test[25] for understanding soil behavior under load and for designing safe and stable structures. These parameters serve as essential input for numerical modelling and ensure accurate representation of soil behavior in simulations.

The 8 sites were divided into two areas of 4 sites according to the revealed subsoil conditions. The first area (Area 1, Yarmouk district, 33.299, 44.340) is about (6 m) of medium brown lean to fat silty clay overlaying medium dense to dense grayish and brownish fine-grained silty sand. Whereas, the second area (Area 2, Mansour district, 33.3191, 44.354) was about (6 m) of medium brown lean silty clay to 12 m of stiff lean silty clay overlaying dense grayish and brownish fine-grained silty sand. Sand with an SPT of 10–30 is classified as medium dense, and dense sand has an SPT between 30 and 50 blows; these ranges are well known and used to classify the soil profile[26,27]. The measured water table at the time of site investigation for areas 1 and 2 was shallow, about 1.5 m and 3.0 m, respectively. These are a general overview of the soil profile, and a more detailed description is presented in Fig. 2. Table 1 summarises the average subsoil parameters for areas 1 and 2.

Materials and methods

Sand columns

Stone and sand columns are generally used for soft ground improvement and are used on a large scale by engineers. However, new methods have been considered to increase the bearing capacity of soil and the settlement of shallow foundations on medium silty clay stratum in the construction of sand columns. Therefore, modified sand columns are adopted, in which sodium silicate sand columns have been used in research on soft clay. Numerous researchers have applied small-scale model tests using sand columns and sand columns stabilised with additives to improve the soft soil properties[6,8,28,29]. Other researchers have used FEM[6,8–10]. All these studies reveal that the ultimate bearing capacity of the soil with the stabilized sandstone and sand column increases when compared to that of ordinary sandstone and sand column. These studies, however, do not indicate the usage of certain columns stabilised with additives on medium silty clay, as has been observed for weak clay and soft clay. It is worth noting that previous studies focus on soft clay soil with an allowable bearing capacity of less than 50 kPa, not on medium clay soil with an allowable bearing capacity of 50 kPa to 100 kPa. Therefore, the replacement rather than displacement method can be applied in the construction of the sand column. Furthermore, Al-Khalidi et al.[7] have used sand columns stabilized with sodium silicate have proved significant improvement ratio in bearing capacity of treated sand column compared to unstabilized columns.

The construction procedure of the sand columns for floating and end bearing started directly using the replacement method. This generally consists of a wet process using the vibratory probe with a water jet into the soft clay layer to make a circular hole that extends through the clay to firmer soil (i.e.[1,2,28]). The hole is then filled with imported sand. The sand in the hole is gradually compacted as the vibrator is withdrawn. The curing time of sodium silicate-treated columns influences the effectiveness. While longer is generally better, there is likely an optimal curing time for specific soil types and applications. Javadzadeh[30] has shown significant improvement after 14 days, reaching peak strength around 28 days. Inadequate curing leads to weaker gel formation and lower performance[30]. However, it is worth mentioning that the treated sodium silicate sand sample soaked and dried for more than 60 days without any changes to the initial form of the cubic shape. Fu[31] highlighted the risk

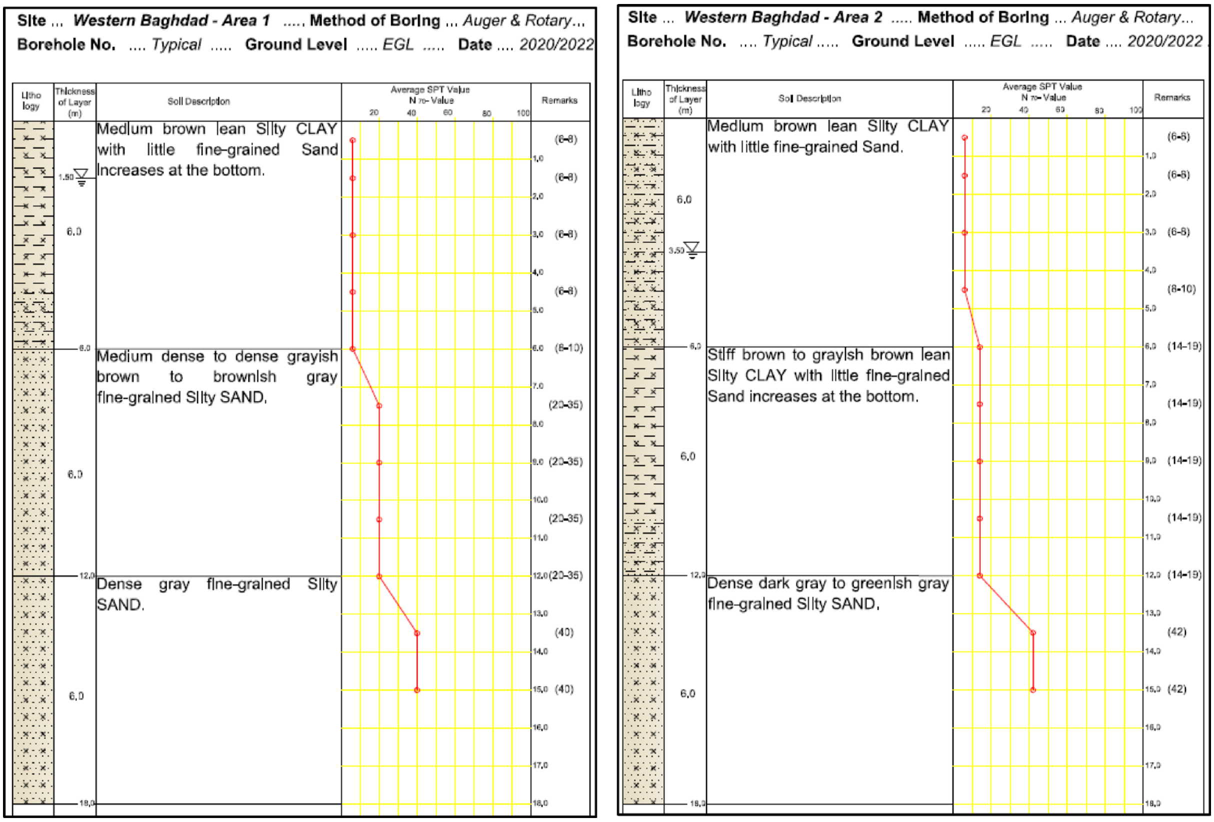

Fig. 2. Typical soil profile for Western Baghdad, (left) Yarmouk Area 1[6] and (right) Mansour Area 2.

Geotechnical parameters	Yarmouk area 1		Mansour area 2		
	Value				
	Clay (0–6 m)	Sand (6–20 m)	Clay (0–6 m)	Clay (6–12 m)	Sand (12–20 m)
Cohesion (c), kPa	30–40	0–8	30–40	50–65	0–10
Friction Angle (φ), °	0–3	25–35	0–5	0–3	30–40
γ_{dry}, kN/m^3	14.0–15.0	15.0–16.0	14.0–15.0	14.0–15.0	15.5–16.5
Water content (w_C) %	24.0–28.0	16.0–20.0	22.0–25.0	22-0.0–26.0	18.0–22.0
Void ratio (e_o)	0.650–0.750	0.429-0.536	0.630–0.800	0.600–0.700	0.483-0.589
Compression index (Cc)	0.22–0.26	-	0.17–0.24	0.18-0.22-	-
Rebound index (Cr)	0.035–0.045	-	0.038–0.050	0.030–0.040	-
Cv, cm^2/min × 10^{-2}	30.8–52.4	-	84.8–98.7	20.2–25.4	-
USCS	CL – CH	SC – SM	CL – ML	CL-ML	SC-SM
K_s, kPa/m	7400–9800	14,000–22,000	8000–9800	13,400 – 12,600	12,000–22,000

Table 1. Physical properties of soil for areas 1 and 2.

of silicate dissolution over time, recommending hybrid stabilisation for durability. Therefore, cement can be present in sodium silicate-treated soils exhibit higher strength values with longer curing times. Therefore, the work could be extended to investigate short-term and long-term effects of sodium silicate on soil behaviour and durability in the future.

Sand columns usually have diameters of 0.5 to 0.75 m and are spaced at about 1.5 to 3 m centre to centre (i.e.[1,2,28]). Therefore, sand column techniques have been used extensively to establish a solution for the bearing capacity problem of weak soil. Larger diameters (D) and optimal spacing (S), which are typically 2.5–3 times the sand column diameter, improve load distribution. Length to diameter (L/D) ratios of 4–6 are ideal for end-bearing columns, and (L/D) 8 for floating ones. Al-Khalidi et al.[3] provide parametric evidence through PLAXIS 3D modelling. Therefore, their results showed that a minimum of 0.07 area of footing can lead to a significant enhancement of the bearing capacity and settlement.

In the current study, the suggested practical method of the implementation of the sand column is using the multi-drill method, using a continuous auger drill and the rotary drilling method using a wash drill method to make a 200 mm diameter circular hole[20,21]. Then, the sand was mixed with sodium silicate and filled the borehole using the drilling bit and rod, with the continuous dynamic pressure by the hammer used for the standard penetration test, dynamic pressure by the hammer used for SPT is processed up to 5 bars. From a practical point of view, with construction of such sodium silicate sand columns in this study would cost significantly less than if the pile foundation is used. Therefore, the pile would cost fivefold compared to sodium silicate sand columns in Baghdad, Iraq. As the bottom end of the sand column rests on a medium silty clay layer of bearing capacity of 70–90 kPa or rests on a medium dense to dense fine-grained silty sand layer of bearing capacity of at least 100–130 kPa, therefore, it can be named as end bearing sand column.

Finite element method (FEM)

A basic idea of finite element methods is to divide the structural body into small and geometrically simple bodies, called elements, which are assumed to be connected by nodes located on the elements' edges and vertices. Equilibrium equations of each element can be written, and all are solved simultaneously to find unknown discrete values (displacements at the nodes) rather than to solve unknown functions (displacement fields). As the displacement on each node is a vector and has two components (in 2D cases), the number of total unknown quantities to be solved is two times the number of nodes.

Plaxis is a FEM intended for the 2D or 3D analysis of deformation, stability, dynamics, and groundwater flow in geotechnical engineering[32]. The FEM is an approximate calculation technology for engineering problems such as stress analysis, heat transfer, and the flow of fluid and electromagnetic[33]. The acceptance of numerical analyses in geotechnical problems is increasing, and the calculation of finite elements is more widely used in foundation design[34]. In the present study, the behaviour of layered soils reinforced with sodium silicate sand columns was studied systematically. The footing was modelled as linear elastic materials, while the soil was modelled in the Mohr-Coulomb (MC) model. The MC model was adopted for its simplicity and suitability in capturing essential shear strength behaviour in both fine-grained and granular materials. It is particularly effective in preliminary or comparative numerical studies[35]. While traditional, its application in this context focuses on chemically stabilised columns in medium clay, which offers practical insights for geotechnical engineers[35]. The parameters for the sand column stabilised with sodium silicate (such as cohesion (C), angle of internal friction (ϕ), modulus of elasticity (*E*), and unit weight (γ) were derived from experimental studies reported[3,6,7]. These studies demonstrated how sodium silicate increases the unconfined compressive strength of sand and improves bonding between sand grains, thus enhancing overall stiffness and strength. The ultimate capacity of the foundation was defined from the load-settlement curve according to the (100 mm) method (i.e.[1,2,36,37]). Two areas of different soil profiles were used in this simulation, as illustrated in Fig. 3.

Models were modified and created with Plaxis 3D to investigate the soil bearing capacity and settlement characteristics of the foundation on the soil layer reinforced by a sand column with sodium silicate in floating and end-bearing types. Provided with a standard fixity option in PLAXIS 3D, the boundary conditions of the model at the bottom of the soil model were restrained in horizontal and vertical directions, even though different software has been adopted in their research ($u_x = u_y = 0$)[37,38]. However, at the left and right boundary of the soil model, horizontal movement is restrained and free to move in the vertical direction ($u_x= 0$, $u_y \neq 0$)[38,39]. The interface between the sand column and soil was simulated by the use of an interface element, and the 10-node tetrahedral element was used.

The analysis is conducted in three stages (phases) of construction. In the first stage, the geometric model with dimensions is created, and geostatic stress is considered. In this study, two areas were chosen for different soil layers. The first area consists of two soil layers, while the second area consists of three soil layers. The hydraulic head is under the soil profile because the water condition is not considered in the model. Further, in the second

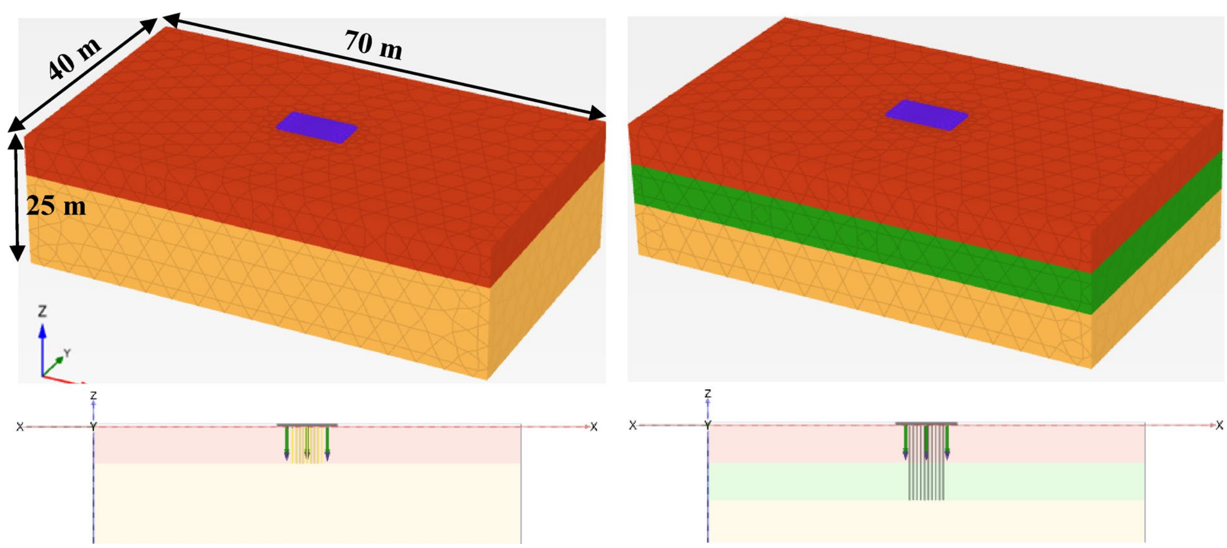

Fig. 3. Numerical soil model 3D (left) two-layer and (right) three-layer soil profile.

Parameter	Footing
Material type	Concrete
Unit weight (kN/m^3)	24.0
Material model	Linear elastic
Young's modulus, E (kPa)	23.5×10^6
Poisson's ratio,	0.15
Drainage type	Non-porous

Table 2. Typical parameters of the used footing in FEM.

Properties	Sand with sodium silicate
Unit weight (kN/m^3)	17.20
Material model	Mohr-Coulomb (MC)
Drainage type	Drained
E, (kN/m^2)	250,000
Poisson's ratio,	0.30
Cohesion, ′ (kPa)	700
Friction angle, ϕ′ (degree)	42

Table 3. Parameters of sand columns treated by adding 8% of sodium silicate[3,7].

Geotechnical parameters	Clay (0–6)m	Sand (6–20) m
Cohesion (c) kPa	36.0	0
Angle of internal friction (ϕ), degree	1.50	33.0–37.0
γ_{dry}, kN/m^3	15.0	15.875
Water content (w_C) %	25.125	16.75
Void ratio (e_o)	0.7187	-
Compression index (Cc)	0.2075	-
Rebound index (Cr)	0.0375	-
Soil Classification according USCS	CL-CH	SC-SM
Ks, kPa/m	8862.5	17,600

Table 4. Parameters of the soil layer when the depth of the clay layer is 6 m (Yarmouk area 1).

Geotechnical parameters	Clay (0–6) m	Clay (6–12) m	Sand (12–20) m
Cohesion (c) kPa	36.0	57.25	2.50
Angle of internal friction (ϕ), degree	1.50	3.25	37
γ_{dry}, kN/m^3	15.0	15.625	16.5
Water content (w_C) %	25.125	26.0	17.0
Void ratio (e_o)	0.7187	0.675	-
Compression index (Cc)	0.2075	0.19625	-
Rebound index (Cr)	0.0375	0.041	-
Soil Classification according USCS	CL-CH	CL	SC-SM
Ks, kPa/m	8862.5	10,825	21,750

Table 5. Parameters of the soil layer when the depth of the clay layer is 12 m (Mansour area 2).

stage, the sodium silicate columns were constructed (all the sodium silicate columns have a diameter of 200 mm and three different lengths (L) to diameter (D) ratios where L/D = 15, 30, and 60 according to each case and the spacing between columns centre to centre greater than 3D. Furthermore, in the third stage, the footing dimension (5 m × 10 m) of area (50 m^2) with a thickness of 0.7 m will be placed on the top surface of the soil at the centre of the model. A medium mesh is generated in the geometry, with mesh refinement generated at the volume of the foundation is the most important to study. Then, in the fourth stage, the loading is applied in the form of a displacement control approach. Tables 2, 3, 4 and 5 summarises the average footing, sand with sodium silicate, and subsoil parameters for areas 1 and 2. In the current study, sixteen FEM models of sodium silicate stone columns were created: twelve columns, twenty-five columns, fifty columns, and seventy-five columns, and such configurations for 12 columns, illustrated in Fig. 3. These tests were modelled with area replacement (A_{sc}/A_{raft}) to the area of the raft foundation of 0.7536% (12 columns), 1.57% (25 columns), 3.14% (50 columns), and 4.71% (75 columns) area of the raft foundation. In addition, the raft foundation model was created to compare it with that of sand column models. The models were simulated using the geometry of 70 m in length (x) and 40 m in width (y), 25 m in depth (z) as illustrated in Fig. 3, selected depending on the loading on the foundation, the soil around the position of loading which be affected and may be disturbed, and the zone of this disturbance varies with loading method and soil density. However, previous studies have revealed that the zone of disturbance was in the range of (3 to 8) of foundation width (i.e.1,2). The numerical outcomes were compared with published model test data from the same author[3,6,7], which involved sodium silicate-treated sand columns in medium clay. The observed settlement of the footing and bearing capacity values of the soil showed strong agreement with this study simulation results, enhancing the model's credibility. Notably, FEM validation against an experimental study. Efforts have been made to validate simulation results by comparing them with published experimental and field data. Al-Khalidi et al.[7] provide settlement and bearing capacity data from model tests on sodium silicate-treated sand columns in clay soils, which correlate well with our numerical predictions. This comparison enhances confidence in the model's accuracy. Further validation using field tests is planned for future work to strengthen these findings.

For medium to high multi-story buildings, the dynamic effect is important. However, it is worth noting that the City of Baghdad according to seismic hazard map of Iraq after Iraqi seismicity code 2017 report[39] of Ministry of Construction, Housing, Municipalities, and Public Works of Iraq is in zone II of 2% probability's peak ground acceleration of 0.2 g in fifty years which would mean its earthquake effect less impact on the stability of the medium multi story building[39]. Therefore, the study did not take the dynamic analysis into consideration.

Results and discussion

For comparison purposes, the load-settlement curves for all the cases of different area replacement ($A_r = A_{sc}/A_{raft}$) total area of sand column the to the area of the raft foundation of 0.7536% (12 columns), 1.57% (25 columns), 3.14% (50 columns), and 4.71% (72 columns) with sodium silicate in floating and end bearing types are adopted, also the results of the raft foundation only are incorporated in the figure shown below. Also, though not presented all here, the corresponding evolution of deformation patterns in the soil layers is provided, which helps to identify the different regions of soil failure in the soil-sand column profile. Moreover, the authors wish to point out that the ultimate load combined both friction and the end of the sand column.

Load-settlement relationship

Floating type columns

Figures 4 and 5 were obtained from the FEM results of a floating type sodium silicate sand column in two and three-layer soil profiles. The pressure–settlement curve for the floating type sodium silicate sand column of L/D = 15[6] and L/D = 30 in medium clay and stiff clay layer, respectively, obtained from the calculated values from the FEM test. The pressure–settlement curve results of the raft foundation only and with the sodium silicate sand column agree very well qualitatively, as illustrated in Figs. 4 and 5.

The ultimate bearing capacity (q_u) of a 3 m length floating type sodium silicate sand column (L/D = 15) in the two-layer profile of a medium clay layer of 6 m depth overlying a dense sand layer slightly increases with the amount of sodium silicate sand column[6]. The maximum increase of the ultimate bearing capacity (q_u) at the maximum allowable settlement for a raft foundation of 100 mm[1,2] reached 10% in which the ultimate load

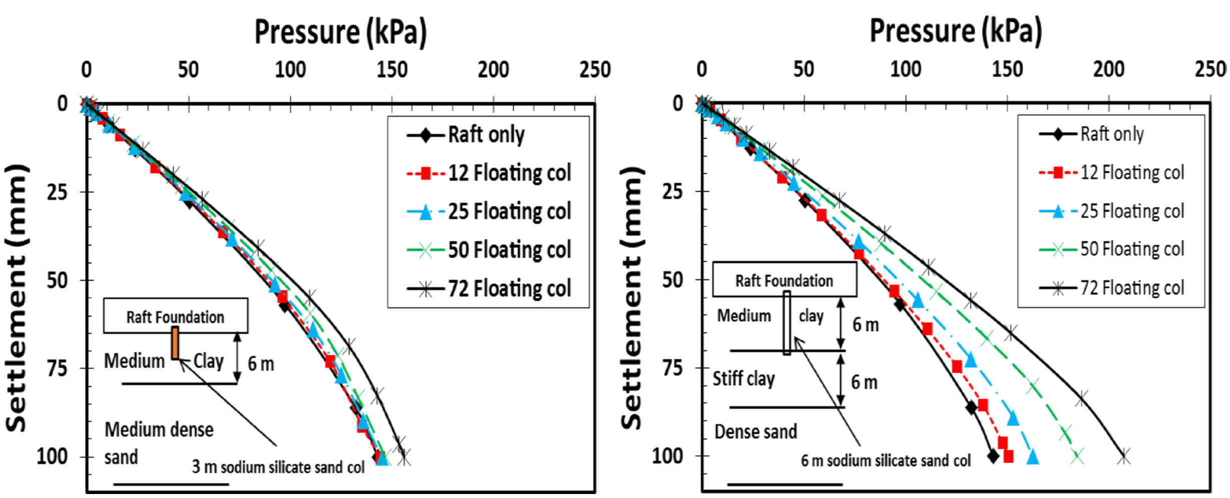

Fig. 4. Pressure settlement curves for floating type sand column (left) two-layer, Yarmouk area 1 for comparison[6] (right) three-layer soil profile, Mansour area 2.

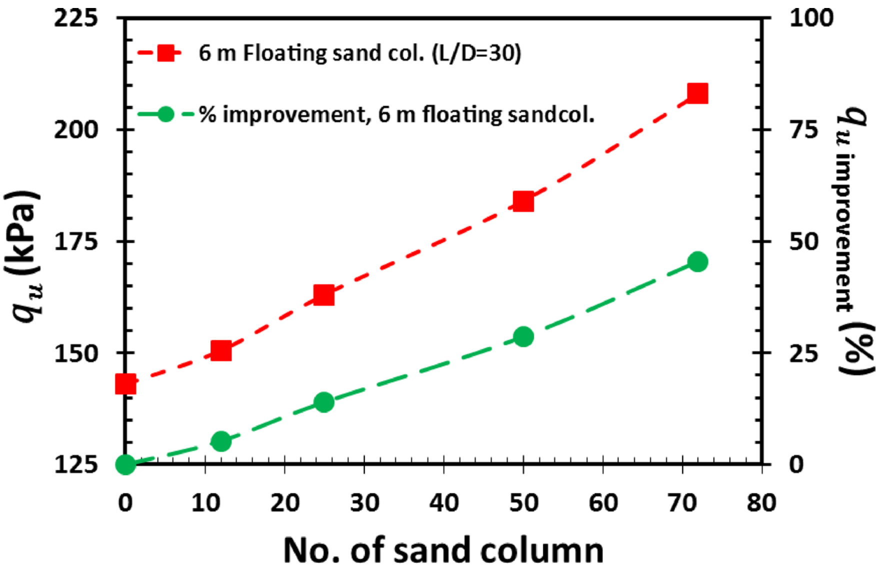

Fig. 5. Comparison of the variation of floating type sand column number with ultimate bearing capacity and improvement percentage[6].

which combined both friction and end of the sand column (Eq. 1 and Fig. 4) for 4.71% (72) sodium silicate sand columns under the raft foundation. Although the results of the modification of sand column with sodium silicate are largely predictable and confirm already known trends, such as the limited effect of floating columns. However, the well performance for most 6 m lengths (L/D = 30) floating sodium silicate sand columns in the three-layer profile of medium and stiff clay layers overlying dense sand, it can be seen that the ultimate bearing pressure (q_u) notably increases with the number of sand column and the improvement reached 50 per cent for 72 sodium silicate sand column under the raft foundation.

It is not presented here, that the analysis of stress ratio between the sand column and surrounding soil, the distribution of axial force along the column, and the shaft–base load ratio is important as they directly affect load transfer mechanisms, settlement behavior, and overall bearing capacity of the improved soil. However, these results are comparable with model test data, which involved sodium silicate-treated sand columns in medium clay[3] enhancing the model's credibility. Additional field validation is planned for future work. This is planned to be addressed in future research. In addition, a field pile load test comparing sand columns stabilized with sodium silicate to untreated piles is intended to be conducted, which will provide further validation of the numerical and experimental findings.

$$q_{u})_{improvement}\ \ (\%) = \frac{q_{u})_{Raft\ on\ sand\ column} - q_{u})_{Raft\ only}}{q_{u})_{Raft\ only}} \times 100 \qquad (1)$$

The quantitative behavior of the sand column in the medium clay layer and in the stiff clay layer for floating type has significant differences. This behavior is probed in the curve illustrating the ultimate bearing capacity (q_u), and the percentage improvement of ultimate bearing capacity ($q_{u\ improvement}$) is depicted in Fig. 5. The floated sand columns with (L/D = 15) adopted in the medium clay soil layer do not give any significant improvement[6]. Based on the results, the floated sand columns with a length-to-diameter ratio (L/D = 15) utilized in the medium silty clay soil layer are not advised to increase the treated soil's ultimate bearing capacity (q_u). Furthermore, Fig. 5 shows that for a floating column with 6 m (L/D = 30), the results are higher than 3 m floating column (L/D = 15)[6]. It is well known that as the length of the sand column increases, the friction also increases. It seems that the reason for these results may be attributed to the interface between the sand column and soil, which indicates well modeled the interface between the sand column and soil. The results are doubled and there are many differences, because it is quite well known that the skin friction of floating sand columns significantly affects the bearing capacity; in addition, the floating within a medium clay layer overlying medium dense sand and confirm already known trends, such as the limited effect of floating columns.

End bearing type columns

Likewise, Figs. 6 and 7 were obtained from the FEM results of end-bearing type sodium silicate sand columns in two and three-layer soil profiles. The pressure–settlement curve for the end-bearing type sodium silicate sand column of L/D = 30 and L/D = 60 in the dense sand layer was obtained from the calculated values from the FEM test. The pressure–settlement curve results of the raft foundation only and with the sodium silicate sand column agree very well qualitatively, as illustrated in Fig. 6. The results from the pressure–settlement curve for different numbers of end bearing type sodium silicate sand columns were used to validate the appropriateness of the

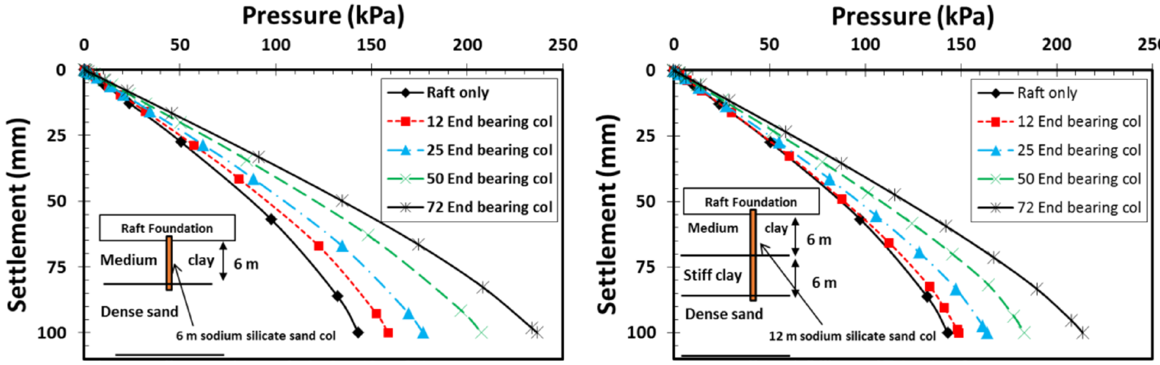

Fig. 6. Pressure settlement curves for end bearing type sand column (left), two-layer (right), three-layer soil profile.

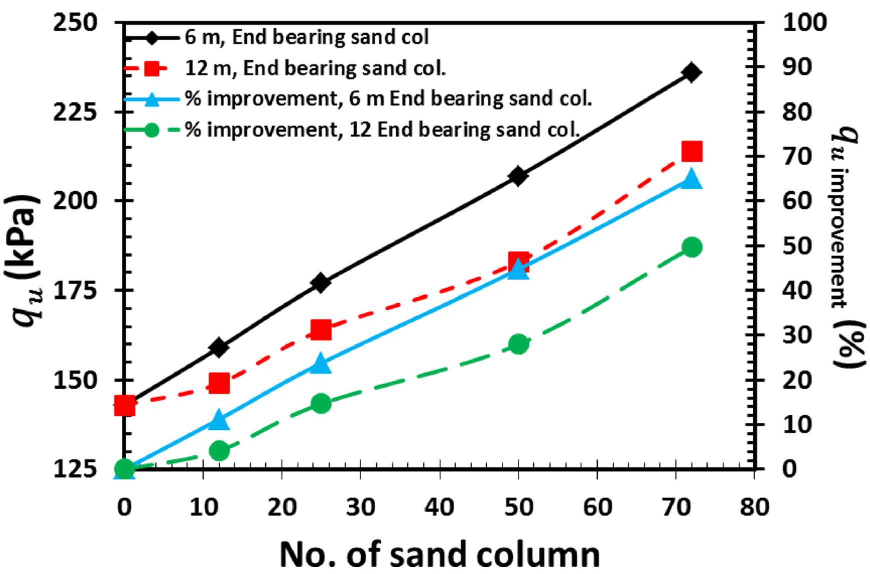

Fig. 7. Comparison of the variation of end bearing type sand column number with ultimate bearing capacity and improvement percentage.

commonly used sand column of L/D less than or equal to 30 and L/D greater than 30 in the FEM compared to the ultimate bearing capacity of the raft foundation only.

The ultimate bearing capacity (q_u) of a 6 m length end bearing type sodium silicate sand column (L/D = 30) into a layer profile of 6 m stiff clay layer depth overlying dense sand layer has significantly increased with the number of sodium silicate sand columns (Fig. 6).

The maximum increase in the ultimate bearing capacity (q_u) at maximum allowable settlement for a raft foundation of 100 mm[1,2] reached 65% (Eq. 1) for 72 end-bearing sodium silicate sand columns under the raft foundation as illustrated in Fig. 6. However, for most 12 m length (L/D greater than 30) end bearing sodium silicate sand columns in the three-layer profile of medium and stiff clay layers overlying dense sand, it can be seen that the ultimate bearing pressure (q_u) improves with the number of sand column and the improvement percentage reached 49 per cent for 72 sodium silicate sand column under the raft foundation. It seems that a reverse behavior was noticed in which the bulging resistance due to confinement affects the 12 m-long end-bearing sodium silicate sand column in a three-layer profile[32].

There is a difference between the end bearing sodium silicate sand column into a dense sand layer and the end bearing sodium silicate sand column into a stiff clay layer overlying dense sand. This is evident in the behavior curve representing the ultimate bearing capacity (q_u) and ultimate (q_u increasing percentage as shown in Fig. 7. The end bearing sodium silicate sand column with (L/D = 30) adopted into the dense sand soil layer has a significant improvement compared to other cases. The end bearing sodium silicate sand column is embedded at the site in research majorly in clayey soil about 12 m, and the skin friction for the cohesive soil the strata of area 1 and area 2 is high. As theoretically, the end bearing sodium silicate sand column in compression embedded in cohesive layer gains its major strength from the sand column's skin friction, it is expected for the skin friction capacity (Q_f) for the ultimate end bearing sodium silicate sand column's capacity (q_u) is higher than end

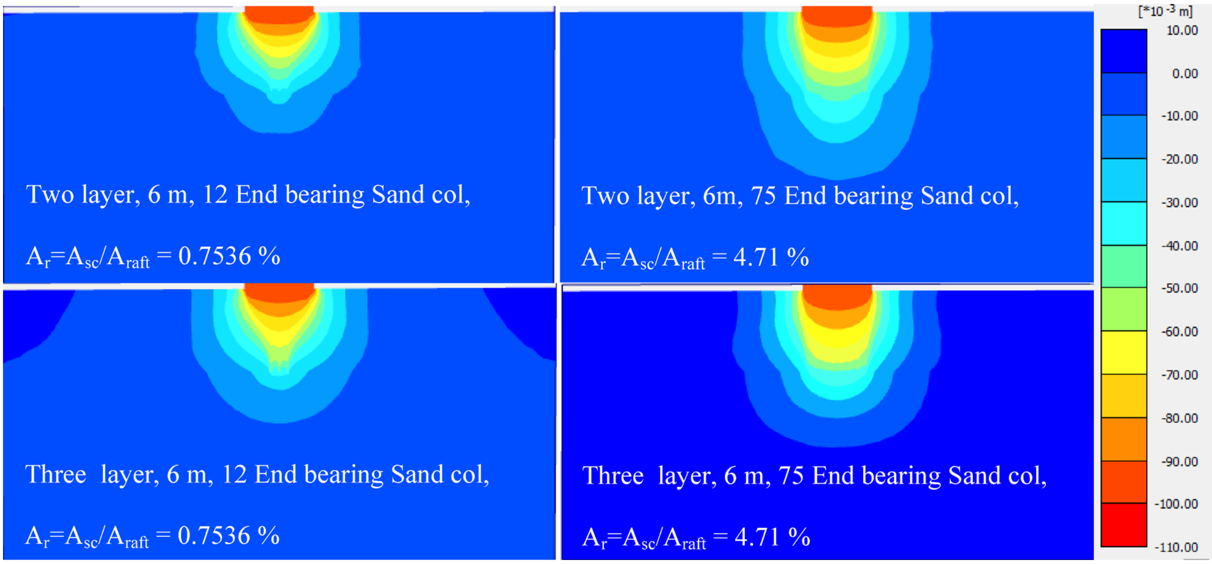

Fig. 8. Comparison of the failure mechanisms of end bearing type sand column.

bearing capacity (Q_b). Furthermore, in the case of sand columns stabilized with sodium silicate, the increased stiffness and cohesion of the surrounding soil may further enhance the contribution of shaft friction to the pile's ultimate capacity. Future studies could quantify the relative contributions of shaft and base resistance using both experimental tests and FEM simulations, providing more accurate guidance for design and optimization of stabilized sand columns in cohesive soils.

Therefore, based on the results, the end bearing sodium silicate sand column with (L/D = 15) adopted into the dense sand soil layer is recommended to enhance the ultimate bearing capacity (q_u) of the treated soil. However, using the 12 m (L/D greater than 30) end bearing sodium silicate sand column can be applied to enhance the ultimate bearing capacity (q_u), but might be costly and time-consuming. This cannot be an alternative approach compared to the pile foundation, which the current research has analysed to enhance the ultimate bearing capacity (q_u) of the raft foundation on sodium silicate sand column that could be used for the multistory building consisting of 7–9 levels. Soil strength is primarily enhanced using chemical gelation of sodium silicate, forming calcium-silicate-hydrate (C-S-H) bonds among sand grains. As a results, cohesion, friction and permeability positively enhanced leads to better stiffness of the sand column such findings were approved (i.e. 3,6,7). The superior performance of improved end bearing columns is quite sensitive to L/D and area ratio as can be seen to the increasing percentage as illustrated in Fig. 7. For end bearing columns, length to diameter (L/D) ratios of 4–6 are generally considered optimal, while for floating columns, a ratio of approximately 8 is preferred. These recommendations are supported by parametric studies, such as the one conducted by Al-Khalidi et al.[7] using Plaxis 3D modeling, which also suggests that a footing area of at least 0.07 can significantly improve bearing capacity and settlement.

Failure mechanisms

Figure 8 shows the comparison of the failure mechanisms of the end bearing type sand column from the FEM results, the sodium silicate sand column in two and three-layer soil profiles. The failure mechanisms for the end bearing type sodium silicate sand column of L/D = 30 in medium clay and stiff clay, two and three-layer. The failure mechanisms results were probed with area replacement ($A_r = A_{sc}/A_{raft}$) total area of the sand column to the area of the raft foundation agree very well qualitatively for two and three layers for the same area replacement, for the top and bottom, as illustrated in Fig. 8.

Further, the failure mechanisms results were probed with area replacement of 0.7536% (12 columns) and 4.71% (75 columns) agree very well qualitatively for the same soil profile area replacement, for the left and right, as illustrated in Fig. 8. The depth of the envelope pattern is deeper in the three-layer (area 2) compared to the layer soil profile (area 1), as the strengthening effect of the soil and sand column interaction is endorsed by the FEM. The soil deformation was dominated by a vertical movement of the medium soil layer, while the bearing layer showed less deformation. This confirmed that the sand column transfers the load to the end of the bottom. AS for Plaxis, difficult soil problems were simulated by[40] on gypseous soil and compared very well to particle image velocimetry (PIV), which rectified the application of FEM in numerous research.

Conclusions

The current research presents an investigation of the implementation of sodium silicate sand columns to improve the bearing capacity of medium silty clay soil and the settlement of raft foundations across various two-layer along three-layer soil profiles. The FEM adopted here significantly presents the load-settlement curve results for floated and end bearing types of sodium silicate sand columns. It is noted that the use of end bearing type of sodium silicate sand column contributes considerably to enhancing the ultimate bearing capacity of the medium silty clay soil, and thereby mobilises the footing structure-soil strength in the foundation system. The relations between the sand column types and their load settlement behaviour is simply given in (Eq. 1).

Generally, in both floating and end bearing types of sodium silicate sand columns, behaviour could be mainly affected by the clay soil strength, and geometric condition and less so for end bearing types by the number of the sodium silicate sand column. Hence, the end bearing type reveals a higher improvement of 50–65% compared to the floating type sand column of 10–45 per cent used here. Therefore, the current study showed that the required number of floating type sodium silicate sand columns is to be increased by two times the area of the raft foundation (i.e. $2A_{raft}$ = 100 sand columns). Therefore, the current study showed that the required number of floating type of sodium silicate sand column is to be increased by sufficient area replacement (A_{sc}/A_{raft}) to the area of the raft foundation of more than 5 per cent. Further research is required to illustrate the factors and effects of the floating type of sodium silicate sand column considered here. Furthermore, the present model study has not considered the effects of spacing[8,9] between the columns. Moreover, sodium silicate can leach, reducing effectiveness. Risk is higher in permeable soils and wet environments. Mitigation strategies include clay capping, pH control, and mixing with cementitious materials to enhance gel stability[31]. However, the water level in the studied area is somewhat 1.5–3.5 m depth which has less effect on the sand column embedment length of 3–6 m. Therefore, area replacement (A_{sc}/A_{raft}) of the sand column may be increased rather than length to diameter (L/D) to overcome the substantial effect of the water table.

Furthermore, another negative factor that would result in bulging and the ultimate bearing capacity may be reduced is the length of the simulated sodium silicate sand column. The simulations in this study considered former case of improvement of the bearing capacity of medium silty clay for high buildings, and the connection between the number of end bearing sodium silicate sand columns to the load settlement curve characteristics is likely to be kept at a larger number of columns than considered here.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 6 June 2025; Accepted: 22 October 2025
Published online: 24 November 2025

References

1. Das, B. M. *Principles of Foundation Engineering*, 8th edn (CENGAGE Learning, 2016).
2. Bowles, J. E. *Foundation Analysis and Design*, 5th edn (McGraw-Hill, 1996).
3. Al-Khalidi, E. E., Ahmed, M. D., Sheikha, A. A. & Jahanger, Z. K. Effect of length to diameter ratio on column bearing capacity stabilized with sodium silicate. In *AIP: Proceedings of 3ICGE-Iraq 2022 May 29*, vol. 2864, 030024. https://doi.org/10.1063/5.0186299 (2024).
4. Fattah, M. Y., Al-Neami, M. A. & Al-Suhaily, A. S. Estimation of bearing capacity of floating group of stone columns. *Eng. Sci. Technol. Int. J.* **20** (3), 1166–1172 (2017).
5. Al Saudi, N. K., Al-Gharbawi, A. S., Rajab, N. A. & Tanyrbergenova, G. Sand and stone columns in soft soil at different relative densities. *Japanese Geotech. Soc. Special Publication*. **2** (62), 2121–2126 (2016).
6. Jahanger, Z. K., Al-Khalidi, E. E. & Mandeel, S. A. H. Bearing capacity of medium soil supported raft foundation and treated sand columns with sodium silicate. In *IOP Proceedings of 5CGEE-Iraq and 3ICESE* (2025).
7. Al-Khalidi, E. E., Ahmed, M. D., Sheikha, A. A. & Alshamoosi, A. A. Assessment of bearing capacity and settlement characteristics of compacted clay soil reinforced by sand dune and sodium silicate columns. In *Current Trends in Geotechnical Engineering and Construction: Proceedings of 3ICGE-Iraq* 352–364 (Springer, 2022).
8. Naseer, S., Sarfraz Faiz, M., Iqbal, S. & Jamil, S. M. Laboratory and numerical based analysis of floating sand columns in clayey soil. *Int. J. Geo-Engineering*. **10**, 1–6 (2019).
9. Ambily, A. P. & Gandhi, S. R. Behavior of stone columns based on experimental and FEM analysis. *J. Geotech. GeoEnviron. Eng.* **133** (4), 405–415 (2007).
10. Jamshidi Chenari, R., Karimpour Fard, M., Jamshidi Chenari, M. & Shamsi Sosahab, J. Physical and numerical modeling of stone column behavior in loose sand. *Int. J. Civil Eng.* **17**, 231–244 (2019).
11. Jahanger, Z. K., Antony, S. & Hirani, A. Foundation relative stiffness effects in sand under static loading. In *AIP Conference Proceedings* (AIP Publishing, 2020).
12. Jahanger, Z. K., Antony, S. J., Martin, E. & Richter, L. Interaction of a rigid beam resting on a strong granular layer overlying weak granular soil: Multi-methodological investigations. *J. Terrramech.* **79**, 23–32 (2018).
13. American Society of Civil Engineers. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (American Society of Civil Engineers).
14. Zghair, M. M., Al-Kubaisi, M. S. & Karim, H. H. Using 2D electrical resistivity imaging to evaluate soil investigations in palm towers site of Al-Muthana Airport, Baghdad, Iraq. The Iraqi geological journal. *Dec* **25**, 128–137 (2022).
15. JahanGer, Z. K. Relation between standard penetration test and skin resistance of driven concrete pile in overconsolidated clay soil. *J. Eng.* **17** (5), 65–78 (2011).
16. Ahmed, M. D. & Adkel, A. M. Stabilization of clay soil using tyre Ash. *J. Eng.* **23** (6), 34–51 (2017).
17. Aljorany, A. N. & Noori, F. S. Effect of Pvd and vacuum pressure on saturated-unsaturated soft soils. *J. Eng.* **23** (1), 63–77 (2017).
18. Fatima, B. et al. Sustainable incorporation of Plaster of Paris kiln dust for stabilization of dispersive soil: A potential solution for construction industry. *Constr. Build. Mater.* **397**, 132459 (2023).
19. Hassan, W. et al. Incorporating potassium-rich waste material in a sustainable way to stabilize dispersive clay: a novel practical approach for the construction industry. *Constr. Build. Mater.* **400**, 132717 (2023).
20. ASTM D1452-09. *Standard Practice for Soil Exploration and Sampling by Auger Borings*.
21. ASTM D5783-12. *Standard Guide for Use of Direct Rotary Drilling with Water-Based Drilling Fluid for Geoenvironmental Exploration and the Installation of Subsurface Water-Quality Monitoring Devices*.
22. https://www.google.com/maps/place/Mansour,+Baghdad,+Baghdad+Governorate.
23. ASTM D4746. *Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils*.
24. ASTM D4318. *Standard Test Method for Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*.
25. ASTM D4746. *Standard Test Method for Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading*.

26. Hassan, W., Alshameri, B., Nawaz, M. N. & Ijaz, M. I. Geospatial and statistical interpolation of geotechnical data for modeling zonation maps of Islamabad, Pakistan. *Environ. Earth Sci.* **81**, 1–23 (2022).
27. Hassan, W. et al. Geospatial intelligence in geotechnical engineering: a comprehensive investigation into SPT-N, soil types, and undrained shear strength for enhanced site characterization. *Bull. Eng. Geol. Environ.* **83** (10), 380 (2024).
28. Terashi, M., Kitazume, M. & Minagawa, S. Bearing capacity of improved ground by sand compaction piles. *Deep Foundation Improvements: Des. Constr. Test. ASTM STP.* **1089**, 47–61 (1991).
29. AL-Rubaie, M. S. *Sand Columns Stabilized with Silica Fume Embedded in Soft Clay*. Doctoral dissertation, University of Technology.
30. Javadzadeh, P. The effects of sodium silicate on stabilization of organic soil. *Turkish J. Comput. Math. Educ.* **12** (14), 1774–1782 (2021).
31. Fu, J. *Evaluation of Long-Term Performance of Sodium Silicate Grouted in Embankment Dams* (2019).
32. Bentley. *CONNECT Edition V21.00 General Information Manual* 1–26 (2021).
33. Fish, J. & Belytschko, T. *A First Course in Finite Elements* (Wiley, 2007).
34. Wehnert, M. & Vermeer, P. A. Numerical analyses of load tests on bored piles. In *Proceeding of the 9th International Conference on Numerical Methods in Geomechanics, Ottawa, Canada, August 25–27*, Vol. 1, 1–6 (2004).
35. Kumar, P. & Rao, P. S. Experimental and numerical study of chemically stabilized soil columns. *Geotech. Test. J.* **41** (5), 821–830 (2018).
36. Briaud, J. L. & Jeanjean, P. Load settlement curve method for spread footings of sand. In *Vertical and Horizontal Deformations of Foundations and Embankments* 1774–1804 (ASCE, 1994).
37. Sujatha, S. J., Jahanger, Z. K., Barbhuiya, S. & Antony, S. J. Fabrics-shear strength links of silicon-based granular assemblies. *J. Mech.* **36** (3), 323–330 (2020).
38. Jahanger, Z. K., Sujatha, J. & Antony, S. J. Local and global granular mechanical characteristics of grain–structure interactions. *Indian Geotechn. J.* **48** (4), 753–767 (2018).
39. Ministry of Construction, Housing, Municipalities, and Public Works, Iraq. *Seismic Hazard Map of Iraq Iraqi Seismicity Code 2017* (2017).
40. Jawad, H. M. & Jahanger, Z. K. The effect of oil contaminated on collapse pattern in gypseous soil using particle image velocimetry and simulation. *Civil Eng. J.* **10** (7), 2325–2343 (2024).

Author contributions

Z.K.J.: Administration, Conceptualisation, Supervision, Software, Validation, Methodology, writing-original draft, Writing-review and editing. A.J.N.: Investigation, Methodology, Writing-original draft, Writing-review and editing. E.E.A.: Software, Validation, Methodology, Writing-original draft, Review and editing. A.A.A.: Investigation, Methodology, Writing-review and editing. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Z.K.J.