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Numerical Investigation on the Bearing Capacity Improvement of Shallow Foundation on Salinity Soft Clay Layers

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ABSTRACT

This study utilizes the finite element method (FEM) to evaluate the bearing capacity improvement of a shallow foundation on salinity. Soft soil was improved by adding different types of salt compounds, including NaCl, $MgCl_2$, Na_2SiO_3, $CaCl_2$, and Portland cement with various percentages of 2%, 4%, 8%, and 10%, respectively. The effect of chemical agents on treating the shear strength of saline soil was increased. On the other hand, the increased bearing capacity of treated soil rose from 30 kPa to 265, 254, 490, 360, and 320 kPa for improved thickness H/B in layers treated with sodium chloride, magnesium chloride, Portland cement, sodium silicate, and calcium chloride, respectively. The best depth of the treated layer was H/B for all cases. The bearing capacity improvement ratio of improved soil increased to 16 times that of the original soil. Based on the results, the model provides calculations from Plaxis-3D that closely align with Terzaghi's equation. An isobar is a line that connects locations of equal stress below the ground surface, essentially a stress contour. After improving the top layer, a load applied to the soil surface reduces vertical tensions inside the soil mass. These increased strains are most noticeable just below the loaded region.

1. INTRODUCTION

Foundations play a pivotal role in structures by effectively transferring loads from the surface to the underlying soil, thereby preventing failure of either the soil or the foundation itself. Thus, it's essential to evaluate the soil's bearing capacity. This aspect has garnered significant attention from geotechnical researchers both historically and presently [1-5]. Soft soil foundations often encounter issues like excessive settling and inadequate load-bearing capacity, particularly in soils with Modern engineering practices frequently entail the replacement of weak topsoil with stabilized soil to mitigate the effects of small shear strength, for instance consolidated or considerably over-consolidated clays. However, the load-bearing capacity of layered soil is dependent on the capacities of both its top and bottom layers. Along the banks of the Euphrates River, fine sediment deposits like silt or silty clay, along with mud accumulation, create steep barriers that obstruct river flow. Utilizing river water for various engineering projects like car parks, dams, and bridges is facilitated by stable river banks; unstable banks can cause delays in exploitation. In the southern region of Iraq, soils along the Euphrates River are characterized as saline soft soils, posing challenges for civil engineering applications, particularly when dealing with fine subgrade soils. Using various chemicals to stabilize soil has been the subject of several investigations. Lime and cement stabilization is the standard procedure for stabilizing clayey soil. However, there is reason to investigate low-cost chemicals that may be used to alter soil properties. Ground improvement or ground modification refers to the application of mechanical, hydrological, physicochemical, biological, or any combination of these techniques to alter particular characteristics of naturally occurring soil deposits. Enhancing the permeability or reducing the amount of settlement existing soils is the primary objective of ground improvement. In order to improve the consistency limits and shear strength of saline soft soils, Al-Kinani and Fattah [6] investigated the effects of adding various salt compounds, such as NaCl, $MgCl_2$, Na_2SiO_3, and $CaCl_2$, in varying percentages (2%, 4%, 8%, and 10%), together with Portland cement. The unconfined compressive strength of the soil was found to increase from 290 to 814, 506, 404, 574, and 422 kPa, respectively, and to decrease the consistency limits when cement materials and a group of chlorides, NaCl, $MgCl_2$, Na_2SiO_3, and $CaCl_2$, were added.

Moayedi et al. [7] studied the effect of sodium silicate system binders on the physicochemical characteristics of soft soil. A number of batch tests were conducted. According to the results, adding 3 mol/L of Na_2SiO_3 may raise the unconfined compressive strength (UCS) of soil in group testing by up to 220% of its reference strength, while adding activators $CaCl_2$ and/or $Al_2(SO_4)_3$ can boost UCS values by up to 270%. Additionally, adding $CaCl_2$ at greater concentrations (such as 1 mol/L) had no appreciable impact on the UCS findings.

Al Asadi and Al-Kinani [8] studied the soft soil was treated with salt concentrations of 2%, 4%, 8%, and 10% to observe the effects on consistency limits and compaction properties. The study's conclusions showed that while the optimal moisture content decreased, the highest dry density increased as the amount of each chloride component increased. The plastic limit, plasticity index, and liquid limit all decrease with increasing salt concentration.

For instance, Bhardwaj and Sharma [9] used FEM to expect the bearing farthest reaches of shallow foundations on settled layered soil with various point degrees (L/B) and soil layers. They saw that raising the degree of unsterilized clayey soil impelled a reduction in balance bearing breaking point.

Szypcio and Dołżyk [10] used PLAXIS to analyze four specific earth conditions with two-layered structures of varying thickness ratios, aiming to determine the ultimate bearing capacity of strip and square footings. Their findings identified an optimal thickness ratio (H/B = 2) for evaluating the bearing capacity of such subsoils. Ground improvement efforts focus on enhancing soil strength, minimizing settlement, and modifying permeability. Saline soils, often containing hydrated gypsum ($CaSO_4 \cdot 2H_2O$), SiO_2, calcite ($CaCO_3$), or NaCl, are typically found at the surface. High moisture content, caused by capillary action and diffusion, along with increased water salinity due to salt sedimentation from evaporation, are key factors contributing to saline soil formation [3, 4]. Sharp soils with chloride salt levels beating 3% show high conductivity [5]. Saline particles soak penetrable electric media through water migration and hence team up with soil particles. Chloride particles other than have a wide hydration range and can ingest water. Without fitting treatment, such soil would forget to satisfy improvement rules on account of issues like salt turn of events, breaking down, and immersion ingestion. Chloride particles impact both the microstructure and strength properties of treated soil, applying a fundamental impact on its short and huge length strength [7, 8].

The substantial presence of saline content suggests potential alterations in the geotechnical attributes of clayey soils when subjected to water infiltration. Experiments involving sodium chloride mixed with clayey soils revealed a decrease in both plasticity index and unconfined compressive strength with increasing salt concentrations [9]. Introducing chloride salt notably enhanced the structure of lime-soil blends, augmenting the proportion of coarse soil particles while reducing overall surface area. However, elevating salt levels diminished the homogeneity degree, though a linear relationship was observed between salt quantity and microstructural features such as bone area, appearance ratio, and roundness [10]. Incorporating up to 8% calcium chloride proved beneficial for lateritic soil improvement, although it's not ideal as a standalone stabilizer but rather serves well as a modifier or admixture in cement stabilization for lateritic soil. Research conducted in Shatt Al-Arab Southern Iraq explored the impact the impact of salinity on the engineering properties of fine-grained soil was explored, involving laboratory tests such as Atterberg parameters, standard compaction, consolidation, and soil shear strength analysis. It is worth noting that the presence of discernible levels of suspended salts in water can result in changes to the soil's engineering attributes [11].

The effects of salt solutions with varying concentrations of seawater on the geotechnical characteristics of soft soil scattered in various regions from Mong Cai to Thanh Hoa province have been thoroughly examined by Nguyen et al. [12]. Prior to testing, the undisturbed soil samples were steeped for 10 days in various salt solutions. The findings of the study demonstrate that a rise in seawater proportions raises the soil's salt content. In terms of some geotechnical characteristics, as soil salt content rises, the compression index and vertical coefficient of consolidation rise while the Atterberg limits and the soil's undrained shear strength decrease.

Different studies evaluated the impact of Magnesium Chloride ($MgCl_2$) emulsion on the geotechnical characteristics of clay soils. Turkoz et al. [13] found that increasing the $MgCl_2$ content led to a decrease in soil consistency (Atterberg limits). The addition of NaCl, $CaCl_2$, and $MgCl_2$ was observed to fill the voids between soil particles because the particle size of these compounds is smaller than that of soil particles, facilitating their replacement of voids. As a result, the compression guide and swelling index reduced with increasing chloride compound percentage [14, 15].

2. THE EFFECT OF SALINITY ON SOIL'S PROPERTIES

Because of the comparatively larger concentration of ions around the platelet, the invading water also has a propensity to flow into the spaces between the clay platelets, further separating them. Dispersion occurs when there is too much space between the platelets, which causes the platelets to be swept away by the water moving and could become lodged in large soil pores, further slowing down the rate of absorption. If water cannot get through the top layer of soil, it may expand and become saturated.

Sodium affects soils in the opposite way that salt does. Clay platelet and aggregate swelling and soil dispersion are the main physical processes linked to elevated salt concentrations. The following forces that hold clay particles together are disturbed when an excessive number of big sodium ions pass through them. The clay particles swell and cause soil dispersion when this separation takes place. Therefore, soil dispersion affects the soil's hydraulic conductivity in addition to lowering the amount of water that enters the soil.

Hydraulic conductivity describes how quickly water enters the subsoil. For example, well-defined soils will contain many microspores, fissures, and fractures that facilitate rapid water movement. When soil structure deteriorates due to sodium-induced soil dispersion, hydraulic conductivity is likewise reduced. Hanson et al. [16] explained that the soil dispersion causes clay particles to plug soil pores, resulting in reduced soil permeability. Their ion layers tend to overlap as two platelets get close to one another, and electrical repulsive forces emerge as a result of positively charged clay particles having charged ions "attached" to them, making an effort to repel one another. The clay platelets are often kept apart with forces, resulting in the swelling of the soil.

After clay dispersion from repeated wetting and drying, the soil recovers and hardens into an almost cement-like soil with little to no structure. Surface crusting, decreased hydraulic conductivity, and decreased infiltration are the three primary issues brought on by sodium-induced dispersion.

Shariatmadari et al. [17] investigated how three inorganic salts—NaCl, $CaCl_2$, and $MgCl_2$—affect the geotechnical characteristics of a typical clay soil. Additionally, the impact of adding several percentages of this unique clay mineral—10 and 20 percent—on these characteristics was examined.

The findings suggested that each of these salts might significantly impact the mixes' geotechnical characteristics. Changes in the diffuse double layer of clay particles are the primary cause of these effects.

Due to their tiny size and propensity to group near clay particles, salts that induce saltiness, such as calcium and magnesium, do not have this impact. Because calcium and magnesium fight with salt for the same binding sites on clay particles, they will often retain soil flocculated. The quantity of sodium-induced dispersion can be decreased by increasing calcium and magnesium levels. The layer of sodium ions extends farther from the platelet because sodium ions are less drawn to the platelets than calcium ions are. This increases the space between neighboring platelets and causes greater swelling.

The ion layer does not extend as far from the platelets as it does for sodium ions because calcium ions are more firmly attracted to the platelets. This results in less soil swelling and a shorter platelet separation distance. Therefore, calcium can be used in place of exchangeable sodium to promote infiltration and lessen edema.

3. GEOTECHNICAL PROPERTIES OF THE STUDY AREA

In order to determine the subsurface stratification, the field works for the site's geotechnical soil investigations include drilling three boreholes to a depth of 10 meters below the current ground level, performing the required field tests, and gathering undisturbed and disturbed soil samples for laboratory analysis. Soil samples are tested in a lab to ascertain its engineering and physical characteristics at certain predetermined depths.

Grayish silty clay soils, typical of saline areas in southern Iraq, were sourced from the south of the country. Soil specimens were gathered from a depth ranging between 0.5 to 1 meter within Al-Nasiriyah city, located in southern Iraq (Coordinates: Latitude = 628069, Longitude = 3427088). The study area was selected between the Euphrates riverbank and the public estuary project, a significant development endeavor in Iraq. This project plays a crucial role in conveying saline water for irrigation purposes, as depicted by the blue mark in Figure 1. This location exhibits a strong likelihood of heightened salinization due to the area being exposed to drought conditions. Per the standard specification ASTM D 2487-11, the soil falls under the classification ML (Fine-grained soil). After transferring the samples to the Civil Engineering Departments' laboratories at the University of Thi-Qar, comprehensive geotechnical and chemical analyses were conducted. Table 1 outlines the essential geotechnical and chemical characteristics of the soil.

Figure 1. Satellite image of the location of the test points for samples extraction

Table 1. The geotechnical properties of the tested soil

Soil Property	Value	Specifications
D_{10} (mm)	< 0.0007	
D_{30} (mm)	0.0022	
D_{50} (mm)	0.0037	ASTM D422
D_{60} (mm)	0.0047	
Liquid limit, LL (%)	49	ASTM D4318
Plastic limit, PL (%)	38	ASTM D4318
Plasticity index, PI (%)	11	
Specific gravity, Gs	2.65	ASTM D854
Maximum dry unit weight, $\gamma_{d\,max}$ (g/cm^3)	1.61	ASTM 698
Optimum water content (%)	20	
Undrained shear strength, Cu (kPa) for the natural soil	20	ASTM D2166
Undrained shear strength after compaction (kPa)	145	
Cl (%)	1.5	
Organic matter, O.M (%)	6.78	
Total dissolved salts, T.D.S. (%)	9.2	BS. 1377
SO_3	4.1	
Gypsum content (%)	9.3	
pH	8.41	

4. EXPERIMENTAL WORK

The laboratory tests of the soil samples began immediately after receiving the samples in the laboratory. The tests were conducted in the College of Engineering, Thi-Qar University laboratory. Subsequent laboratory tests were executed to determine the physical and engineering properties of disturbed soil samples. All tests on the site have a high potential for increasing salinization because of the drought that exposed the area. Ultimate bearing capacity for square footing under local shear failure given by Terzaghi is [A5]:

$$q_u = 0.867c'\left(N_c\right)' + q\left(N_q\right)' + 0.4\gamma B\left(N_\gamma\right)' \quad (1)$$

where,
C=Cohesion
y=Unit weight of soil
D=Depth of footing
B=Breadth of footing
N_c, N_q, N_y=Bearing capacity factors

5. SHEAR STRENGTH RESULTS

5.1 The natural soil

The shear strength of soils treated with various additives was evaluated through UCS testing. To achieve the maximum dry unit weight and optimum water content, the samples were compacted in three layers using a Harvard miniature compaction device. Each compacted specimen had a diameter of 33 mm and a length of 70 mm.

The undrained shear strength of the treated soils was assessed by incorporating different additives, including Portland cement, NaCl, $MgCl_2 \cdot 6H_2O$, $CaCl_2 \cdot 2H_2O$, and sodium silicate, at varying percentages 0%, 2%, 4%, 8%, and 10%. The results of these tests are presented in Table 2.

5.2 Portland cement

According to the unconfined compressive strength test, the unconfined compressive strength increased as the percent of common cement increased. However, it was discovered that when ordinary cement was mixed with 8% and 10% of cement mixing, the results were unsatisfactory due to the absence of bonding between the cement and the soil.

Table 2. The undrained shear strength results for different chemical agents

Additive Percentage (%)	Unconfined Compressive Strength (kPa)					
	Natural Compacted Soil	NaCl	$MgCl_2$	$CaCl_2$	Portland Cement	Na_2SiO_3
0	20					
2		282	404	422	682	574
4	20	506	316	352	814	518
8		484	206	304	582	422
10		200	208	250	506	326

5.3 Sodium chloride

The results indicate that sodium chloride—a chemical that forms clusters of tiny particles and binds them together—can dissolve rapidly in water, providing a sufficient supply of salt ions for ionic exchange interactions with clayey soil [18, 19].

Sodium chloride was added at varying dosages of 2%, 4%, 8%, and 10% by weight of the soil. The UCS initially increased from 290 kN/m² to 574 kN/m² with the addition of 2% sodium chloride. However, when the sodium chloride content was further increased to 4%, 8%, and 10%, a decline in undrained shear strength was observed.

5.4 Calcium chloride

Suresh and Murugaiyan [20] provided evidence of solid calcium chloride's remarkable water-absorbing capability. At a relative humidity of 95%, solid $CaCl_2$ can absorb 16.6 times its weight in water. Even at a humidity level of 30%, it can still absorb nearly its entire weight in water.

Calcium chloride has been widely used as a stabilizer due to its ability to modify a material's permeability, compressibility, and strength. Its primary function is to bind and agglomerate fine particles, enhancing soil stability. The addition of 2% calcium chloride increases the UCS of the soil to 422 kN/m². However, when the calcium chloride content was further increased to 4%, 8%, and 10%, a decline in UCS was observed.

5.5 Magnesium chloride

Magnesium chloride, a sea salt, is utilized as a green stabilizer because it doesn't harm humans or animals and doesn't erode concrete, asphalt, or automobiles. Conversely, magnesium has an electrical configuration of 2, 8, 2 and an atomic number of 12. As a result, it possesses two more electrons above the nearest stable noble gas electrical configuration, neon. Magnesium cation (Mg^{2+}) is formed when magnesium prefers to shed two electrons from its outermost shell and acquire a stable electronic state. A $MgCl_2$ molecule is created when two Mg atoms combine with two Cl atoms, transferring two electrons from the Mg to the Cl. Because of this, each atom has a stable octet electronic configuration.

When 2% $MgCl_2$ is added to soil, the UCS increases to 404 kN/m². However, it was discovered that when $MgCl_2$ was mixed with 4%, 8%, and 10% of the salt mix, the results showed a decrease in UCS.

5.6 Sodium silicates

Sodium silicates are polymeric, alkaline, inorganic compounds based on silica. Three fundamental components make up all silicates: water, alkali Na_2O or K_2O (raw material = soda ash or potash), and silica SiO_2 (raw material = sand). The UCS of soil rises to 574 kN/m² when 2% sodium silicates are used. Nevertheless, it was shown that the UCS decreased when $MgCl_2$ was combined with 4%, 8%, and 10% of the salt mixture.

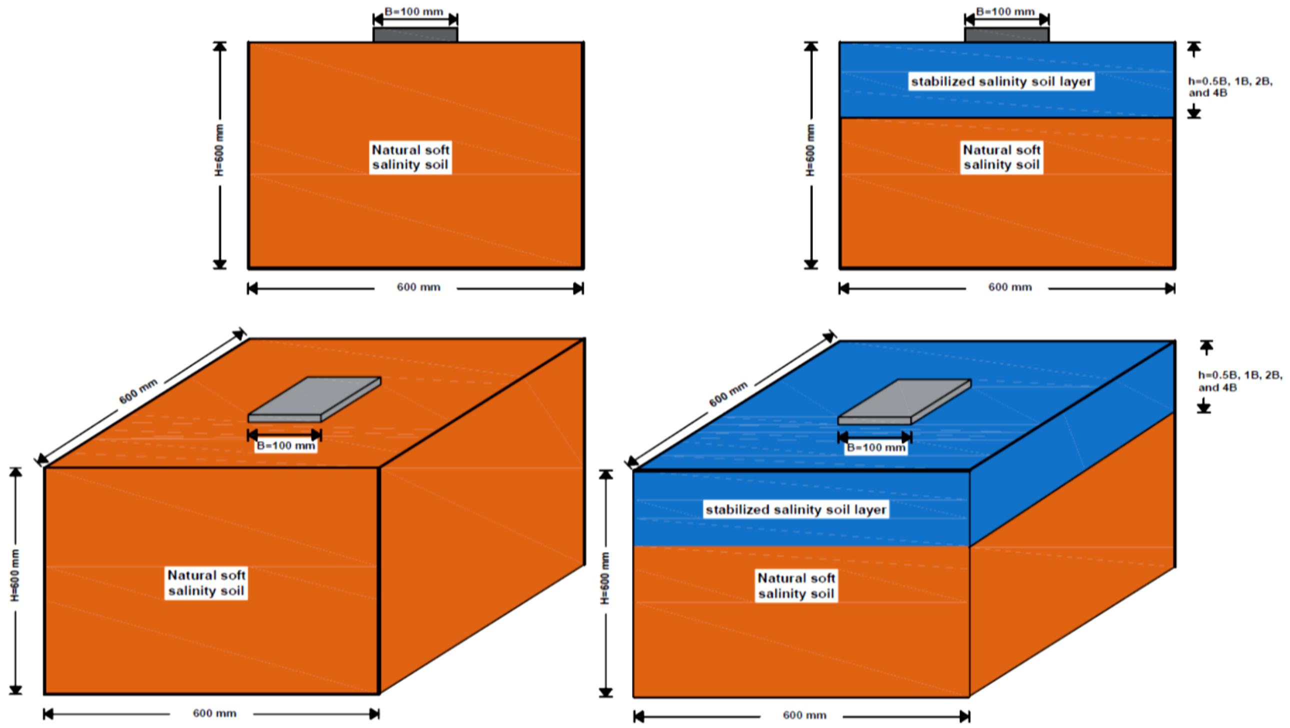
6. PROBLEM STATEMENTS

The project focuses on a shallow surface footing with an aspect ratio (L/B) of 1, where the footing width (B) measures 100 mm. To minimize boundary effects, a clearance of at least 250 mm (2.5 B) was maintained from the footing edges in all directions.

The soil strip dimensions were 600 mm × 600 mm × 600 mm, but the analysis was confined to a smaller square section of the model, measuring 100 mm × 100 mm × 20 mm. In this study, the FEM, implemented in Plaxis-3D, enables the evaluation of complex soil boundary conditions with greater accuracy.

This study encompasses elasto-plastic and elasto-visco-plastic soil behavior models, provided that an appropriate constitutive model is selected. The research focuses on two primary scenarios: one where the footing is supported by a single layer of soft soil, and another where the footing is placed atop a soft clay layer, which is stabilized using various salt compounds, namely NaCl, $MgCl_2$, Na_2SiO_3, Portland cement, and $CaCl_2$, applied at different thicknesses.

The study examines six cases involving a two-layered soil system, with stabilization applied to the weak clay layer in all cases except the first. Local materials, as outlined in Table 3, were used for clay stabilization. The thickness of the upper layer varies according to H/B ratios of 0.5, 1, 2, and 4. Figure 2 illustrates the configuration of soil layers as simulated in the FEM-based software Plaxis-3D.



Note: h - thickness of the upper layer in two-layered soil; L, B - length and width of footing, respectively, all dimensions are not to scale.

Figure 2. Problem definition: (a) Single layer; (b) Thickness of top layer varying at h = 0.5 B, 1.0 B, 2 B, and 4 B; (c) FEM model of footing for aspect ratio (L/B) =1 at natural soft salinity soil; (d) FEM model of footing for aspect ratio h =0.5 B, 1.0 B, 2 B, and 4 B

Table 3. Designation and details of type of soil in upper and lower layers under both types of footings in two-layered soils

Designation	Soil Type in Upper and Lower Layers for Two-Layered Soil		Additive Percentage	Shear Strength cu (kPa)	Layer Thickness (cm)			
Case 1	One layer	Soft clay	0%	20	60			
Case 2	Upper Layer	NaCl	4%	506	5	10	20	40
	Lower layer	Soft clay	0%	20	55	50	40	20
Case 3	Upper Layer	$MgCl_2$	2%	404	5	10	20	40
	Lower layer	Soft clay	0%	20	55	50	40	20
Case 4	Upper Layer	$CaCl_2$	2%	422	5	10	20	40
	Lower layer	Soft clay	0%	20	55	50	40	20
Case 5	Upper Layer	cement	4%	814	5	10	20	40
	Lower layer	Soft clay	0%	20	55	50	40	20
Case 6	Upper Layer	Na_2SiO_3	2%	574	5	10	20	40
	Lower layer	Soft clay	0%	20	55	50	40	20

7. FINITE ELEMENT MODEL

The commercial Plaxis finite element program was utilized as the numerical technique in this investigation. A three-dimensional finite element analysis is called Plaxis 3D. Unless otherwise noted, all analyses in this publication are based on 15 node analysis. The linear soil model, or Mohr Coulomb (MC) model, was used.

7.1 Constitutive models and parametric study

This section does not aim to provide a comprehensive overview of all constitutive models applicable to soft clay soils, nor does it seek to determine the most reliable soil models for clay. Instead, its objective is to outline various constitutive models that effectively represent the mechanical behavior of soft clays and to highlight the importance of specific numerical modeling approaches in accurately describing soft clay behavior.

The MC model (Method B) is employed to simulate geological layers, where stiffness and strength are specified in terms of effective properties. The MC model assumes elastic behavior before failure. The key parameters utilized include E', C_u, or C' for undrained and drained conditions, respectively. It is assumed that clay is normally consolidated (OCR = 1). The MC model is chosen for its simplicity and its ability to predict yielding and strain softening.

Additionally, a linear-elastic model is used for footing analysis. The mesh for all models in Plaxis-3D is generated using a medium element distribution, with a maximum of 256 cores. This study investigates the behavior of two-layered soils beneath a rigid rectangular footing. The footing is modeled as a linear elastic material, while the MC model is used to simulate the saline soil, and a soft soil model represents the lower layer.

The geotechnical properties of soft clay, stabilized clay, and footing materials used in the FEM analysis are detailed in Table 4. Additionally, the study examines a reference case, where the subsoil consists solely of soft soil. Table 3 outlines the specific soil types present in the upper and lower layers beneath both types of footings in two-layered soil systems.

The ultimate bearing capacity of the footing is determined from the load-settlement curve using the 10% B method. Furthermore, the impact of the water table on bearing capacity calculations is not considered in this study.

Table 4. Properties of the materials used in the analysis

Property	Unit	Soft Clay	Stiff Improved Clay with Chemical Agent					Footing-Steel
Model		Mohr-Coulomb	Mohr-Coulomb					Linear-Elastic
Material Type		Undrained B	Undrained B					Nonporous
			NaCl	$MgCl_2$	$CaCl_2$	Portland Cement	Na_2SiO_3	
γ_{unsat}	kN/m³	16.1	15.41					78
γ_{sat}	kN/m³	19.32	18.50					
v	-	0.4	0.2					0.15
c	kN/m²	20	506	404	422	814	574	-
φ	degree	0	0					-
E	kN/m²	7000	126000	101000	10500	203000	143000	27000000
$R_{interface}$	-----	1	1					rigid

8. RESULTS AND DISCUSSION

The aim of this investigation is to assess the impact of varying the height of the upper layer on the bearing capacity and settlement of a square footing placed on a two-layered soil system. The upper layer consists of stiffened clay treated with a chemical stabilizer, while the lower layer comprises soft clay.

The ultimate bearing capacity of the footing is determined through load-settlement analysis using the 10% B method, with settlement limited to a maximum allowable level of 50 mm. Both the footing width (B) and the thickness of the upper layer (H) from the footing center are considered, with H/B ratios of 0.5, 1, and 2, as well as 4 B, being analyzed.

The geotechnical properties of the soils and footing used in the finite element analysis are detailed in Table 4.

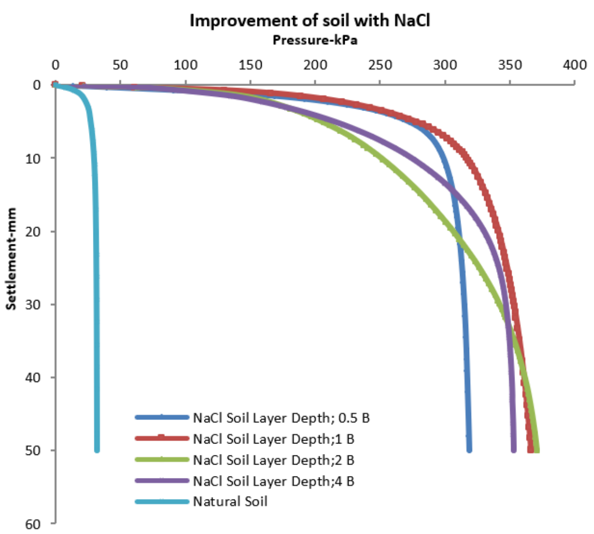


Figure 3. Load settlement curves of square footing resting on layered soil for improved clay with NaCl

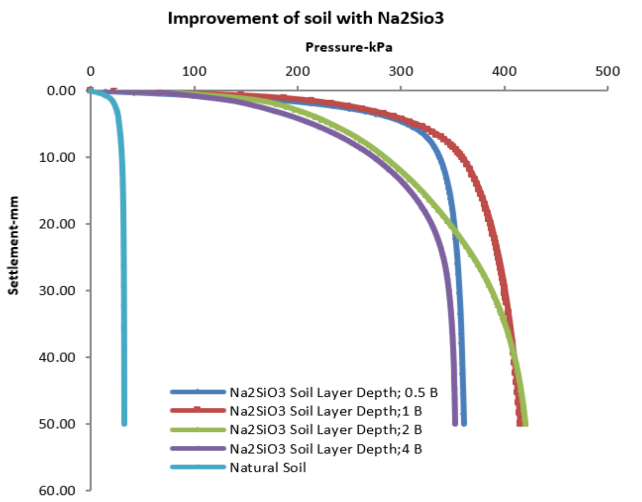


Figure 4. Load settlement curves of square footing resting on layered soil for improved clay with Na_2SiO_3

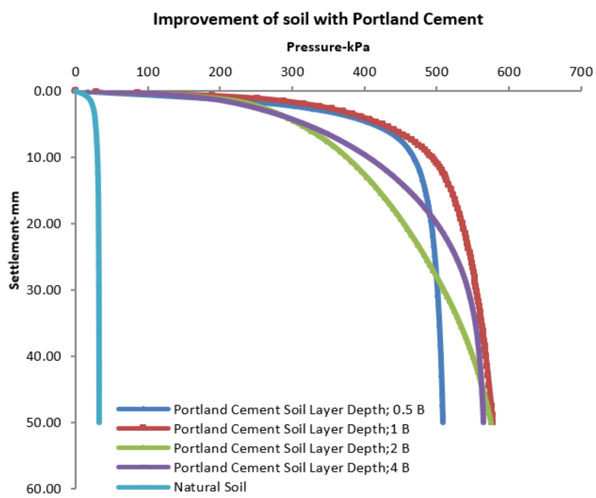


Figure 5. Load settlement curves of square footing resting on layered soil for improved clay with Portland cement

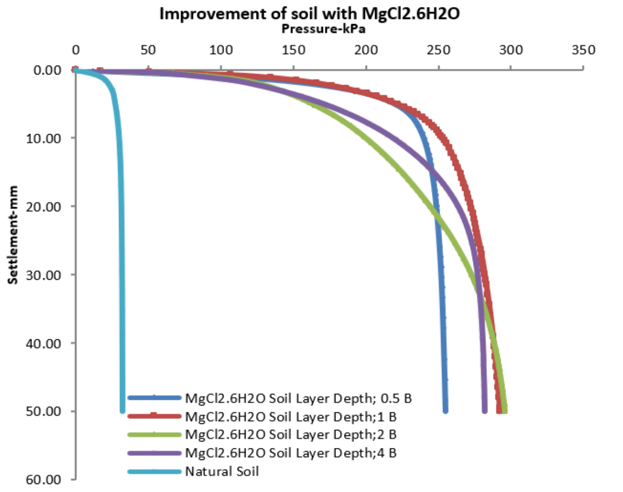


Figure 6. Load settlement curves of square footing resting on layered soil for improved clay with $MgCl_2$

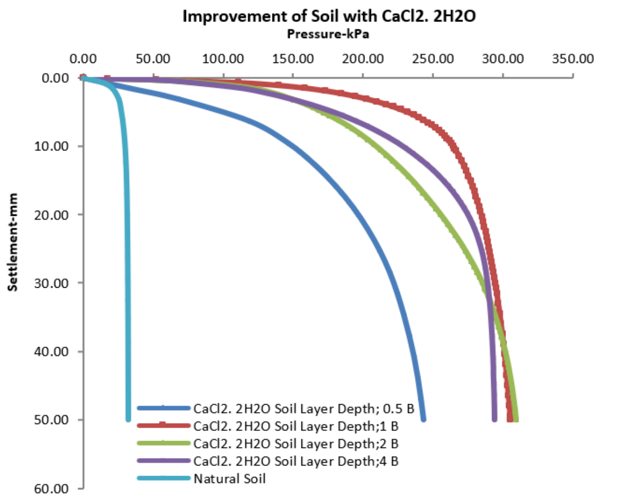


Figure 7. Load settlement curves of square footing resting on layered soil for improved clay with $CaCl_2$

8.1 Load-settlement relationship

Five loading tests were conducted using Plaxis-3D to evaluate the bearing capacity ratio under varying H/B ratios for chemically treated top clay layers. The tests were performed for different cases where the thickness of the strong upper layer (H) varied, specifically at 0.5, 1, 2, and 4 times the footing width (B).

These tests provided valuable insights into the behavior of foundations resting on soft saline soil, with an unimproved foundation serving as a reference to represent natural soil conditions. The ultimate bearing capacities were determined, with failure typically identified when settlement reached 10% of the foundation width. Figures 3-7 illustrate the ultimate bearing capacity q_{mult} for different chemical stabilization agents, including NaCl, $MgCl_2$, Na_2SiO_3, Portland cement, and $CaCl_2$, at varying H/B ratios of 0.5, 1.0, 2.0, and 4.0.

8.2 Effect of depth on bearing capacity

This section investigates the effect of improvement thickness H/B with the ultimate bearing capacity of soil treated with different percentages of chemical agents at failure typically identified by a settlement of 10% relative to the foundation width. These results are shown in Table 5. The effect of change in improved depth on bearing capacity by considering H1/B = 0, 0.5, 1, 2 and 4. It can be seen that the bearing capacity increase from 32 to 150, 265, 210 and 230 kPa respectively by adding $CaCl_2$. When H/B increases from 0 to 1 the bearing capacity increase to 264 kPa, after this point increasing H/B has leads a reduction of bearing capacity to 210 kPa. Also, the bearing capacity increase from 32 to 240, 254, 200 and 220 kPa respectively by adding $MgCl_2$. When H/B increases from 0 to 1 the bearing capacity increase to 264 kPa, after this point increasing H/B has leads a reduction of bearing capacity to 200 kPa. On the other hand, the bearing capacity increase from 32 to 470, 490, 370, and 410 kPa respectively by adding Portland cement. When H/B increases from 0 to 1 the bearing capacity increase to 490 kPa, after this point increasing H/B has leads a reduction of bearing capacity to 370 kPa. While the bearing capacity increase from 32 to 335, 360, and 285 kPa respectively by adding Na_2SiO_3. When H/B increases from 0 to 1 the bearing capacity increase to 360 kPa, after this point increasing H/B has leads a reduction of bearing capacity to 285 kPa.

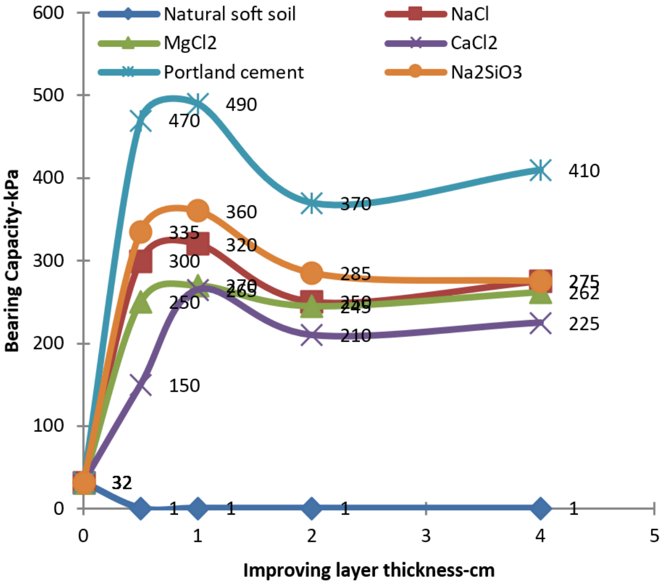
Finally, the bearing capacity increase from 32 to 300, 320, 250, and 275 kPa respectively by adding NaCl. When H/B increases from 0 to 1 the bearing capacity increase to 320 kPa, after this point increasing H/B has leads a reduction of bearing capacity to 275 kPa. So far, the effect of various parameters on bearing capacity of footing on a layered soil has been investigated. It can be seen that H/B= 1 given the maximum bearing capacity in all cases. It means that depth of improved layer (h = B) has much more effective influence on bearing capacity of footing compared with the other depths. The highest soil bearing capacity and most effective improvement ratios are observed at a thickness ratio of H/B equal to 10 cm across all scenarios, as depicted in Figure 8.

Table 5. The variation of the soil bearing (BC) with changing the thickness according to theoretical and numerical methods

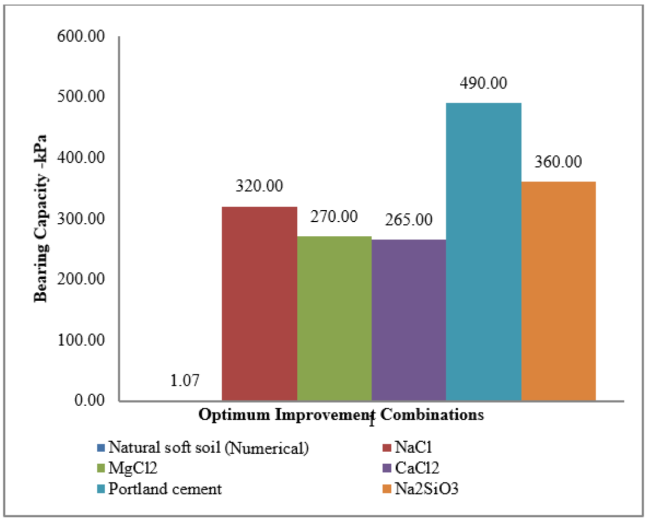
Depth of Improved Layer (H)	Methods	$CaCl_2$	$MgCl_2$	Portland Cement	Na_2SiO_3	NaCl
Terzaghi	Theoretical	30	30	30	30	30
0 B		32	32	32	32	32
0.5 B		150	240	470	335	300
1 B	Numerical	265	**254**	**490**	**360**	**320**
2 B		210	200	370	285	250
4 B		230	220	410	275	275

8.3 Degree of bearing improvement ratio

To evaluate the influence of the improved strong layer on the bearing capacity of the shallow foundation, the theoretical bearing capacity (QT) was normalized against the numerically obtained bearing capacity (QN). The improvement ratio (QN/QT) was plotted in Figure 9, representing the ratio of numerical improvement in bearing capacity (QN) to theoretical bearing capacity (QT) as the depth-to-width ratio (H/B) increases.



(a)



(b)

Figure 8. Bearing capacity values of improving two-layered salinity soil: (a) Pressure–settlement curves fat thickness ration H/B = 10 cm; (b) Optimum improvement combination of two-layered soil for H/B=10 cm

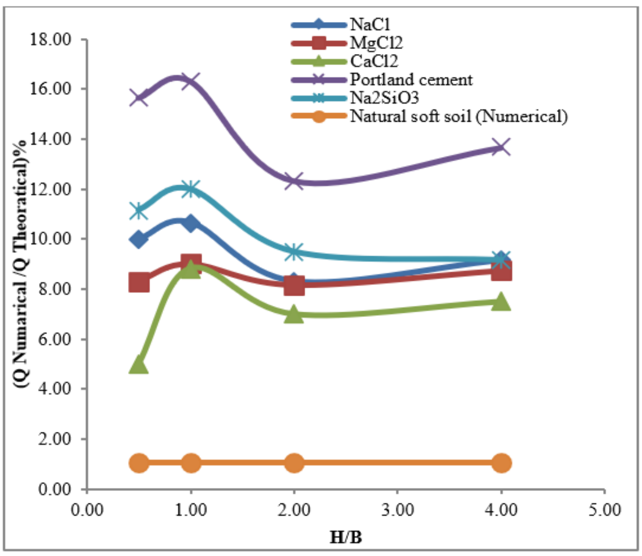


Figure 9. Effect of H/B on bearing improvement ratio

Figure 9 shows that the trend of the improvement ratio is not strictly monotonic. The bearing capacity ratio initially increases with the H/B ratio, reaching its peak at H/B = 1, before gradually declining to a stable level. The graph indicates a linear increase in the QN/QT ratio until the depth-to-width ratio reaches approximately 1.0, after which the improvement ratio stabilizes.

This finding suggests that the optimal thickness of chemically treated saline soil for foundation improvement corresponds to H/B = 1. The maximum improvement ratios observed were 107% natural soil, 1067% sodium chloride, 900% magnesium chloride, 883% calcium chloride, 1633% Portland cement, and 1200% sodium silicate, respectively.

8.4 Displacement contours under foundation

When a load is exerted on the soil surface, it results in increased vertical stresses within the soil mass. These heightened stresses are most prominent directly beneath the loaded area but propagate indefinitely in all directions. Various formulas based on elasticity theory have been utilized to calculate stresses in soils. An isobar, essentially a stress contour, is a line connecting points of equal stress beneath the ground surface. Figures 10-14 illustrate typical displacement contours transitioning from case 1 to case 6 for footings positioned on soft clay, stabilized with different salt compounds such as NaCl, $MgCl_2$, Na_2SiO_3, Portland cement, and $CaCl_2$, at varying thickness ratios of H/B=0.5, 1, 2, and 4. These visualizations offer a comprehensive depiction of displacement contours and their significance in estimating actual displacements under load. The data provided is essential in confirming that the determined thickness ratio H/B=2 is adequate for evaluating the bearing capacity of a two-layered subsoil.

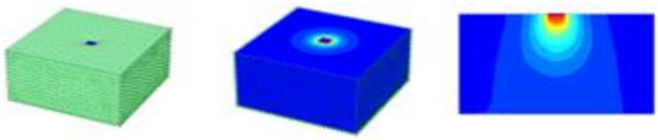


Figure 10. Displacement contours of natural soft soil

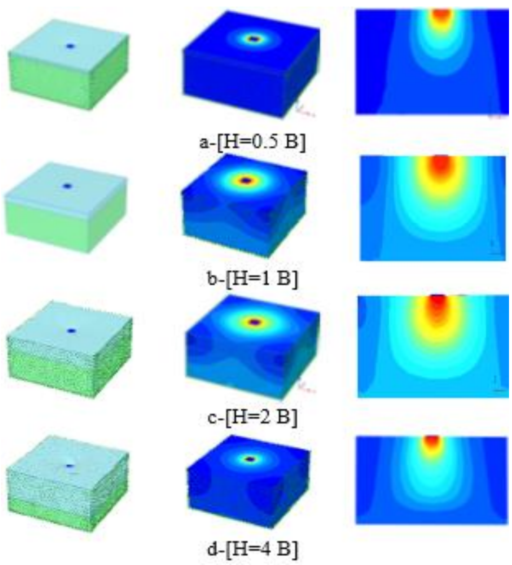


Figure 11. Displacement contours of salinity soils- improved with Na_2Sio_3, with different H/B

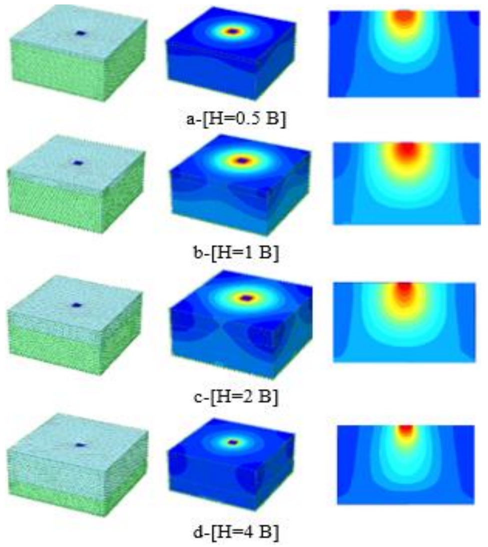


Figure 12. Displacement contours of salinity soils- improved with $MgCl_2$, with different H/B

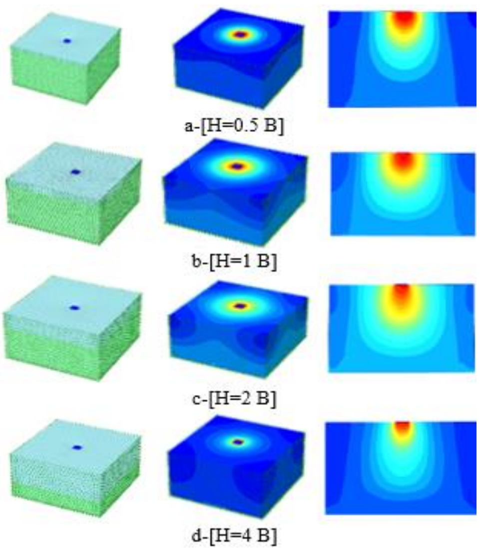


Figure 13. Displacement contours of salinity soils- improved with NaCl, with different H/B

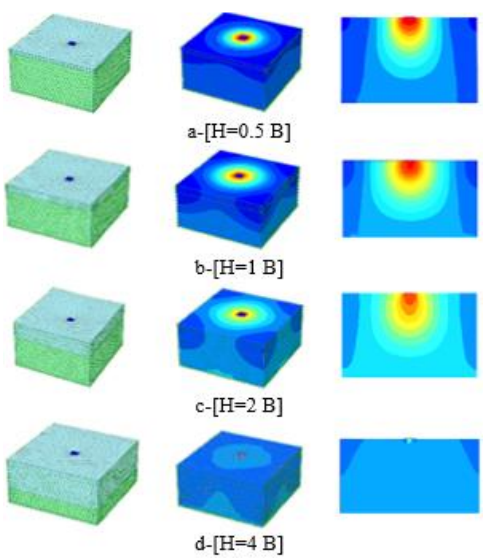


Figure 14. Displacement contours of salinity soils- improved with cement, with different H/B

Additionally, maintaining different H/B ratios 0.5, 1, 2, and 4 within specified limits yields displacement contours for both footings. The isobar distance for the footing with H/B=1 surpasses that of other thickness ratios, indicating a higher ultimate bearing capacity for the latter. Based on the highest soil bearing capacity observed at a depth of H=B=10 cm for all instances depicted in Figures 10-14, it is evident that there exists a pivotal depth below which the strength of the lower layer does not impact the model's bearing capacity. The displacement contours stay within the confines of the initial layer's boundaries when the thickness ratio is H/B=1.

9. CONCLUSION

The analysis of the soil model was carried out to determine the bearing capacity of closely placed square footings resting on improved salinity soil treated by chemical agents' bed using Plaxis-3D. The study investigated the effect of the improved depth thickness, percentage ratio, and chemical agent strength on the bearing capacity. The study concluded that:

•The shear strength of soft saline soils increased with the addition of various chemical agents. The maximum shear strength values recorded were 506 kPa, 404 kPa, 422 kPa, 814 kPa, and 574 kPa for 4% NaCl, 2% $MgCl_2$, 2% $CaCl_2$, 4% Portland cement, and 2% Na_2SiO_3, respectively.

•Chemical stabilization had a significant impact on the bearing capacity of saline-treated soil. The bearing capacity of the untreated soil increased from 30 kPa to 265 kPa, 254 kPa, 490 kPa, 360 kPa, and 320 kPa after treatment with sodium chloride, magnesium chloride, calcium chloride, Portland cement, and sodium silicate, respectively.

•The numerical analysis results showed good agreement with the theoretical predictions based on Terzaghi's bearing capacity equation.

•As the H/B ratio increased, the soil layers treated with calcium chloride, magnesium chloride, sodium silicate, Portland cement, and sodium chloride demonstrated improved bearing capacity. In each case, an H/B ratio of 1.0 was identified as the optimal depth for the treated layer.

•The numerically obtained improvement in bearing capacity was calibrated against the theoretical bearing capacity (QT) to assess the impact of the enhanced upper layer on the shallow foundation's performance.

•The highest improvement ratios recorded for the treated soil layers were 1.07% (natural soil), 10.67% (sodium chloride), 9% (magnesium chloride), 8.83% (calcium chloride), 163.3% (Portland cement), and 12% (sodium silicate).

•An isobar, essentially a stress contour, is a line connecting points of equal stress beneath the ground surface. When a load is applied to the soil surface, the vertical stresses decrease within the soil mass after enhancing the upper layer. These increased stresses are most pronounced directly beneath the loaded area.

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