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Finite Element Analysis of the Influence of Artificial Cementation on the Strength Parameters and Bearing Capacity of Sandy Soil under a Strip Footing

Mohammad T. Alkhamis, Abdulla AL-Rashidi

Department of Civil Engineering, Public Authority for Applied Education and Training, Shuwaikh, Kuwait
Email: aa.alrashidi@paaet.edu.kw

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Abstract

Artificial cementation is a method commonly used to enhance and improve soil properties. This paper investigates the effect of using different amounts of cement on soil strength parameters and soil bearing capacity, using the finite element method. Experimental tests are conducted on soil samples with different amounts of Portland cement. A 2-D numerical model is created and validated using the numerical modelling software, COMSOL Multiphysics 5.6 software. The study finds that the cohesion, and the angle of the internal friction of the soil samples increase significantly as a result of adding 1%, 2%, and 4% of Portland cement. The results demonstrate that the stresses and strain under the strip footing proposed decrease by 3.24% and 7.42%. Moreover, the maximum displacement also decreases by 1.47% and 2.97%, as a result of adding cements of 2% and 4%. The bearing capacity values obtained are therefore excellent, especially when using the 2% and 4% cement. The increase identified is due to the increased values of the bearing capacity factors. It is concluded that from an economic viewpoint, using 2% cement is the best option.

Keywords

Artificial Cementation, Strength Parameters, Bearing Capacity, Finite Element Method, Strip Footing

1. Introduction

The failure of building works, or the creation of poorly constructed works, can be attributed to many different causes, including bad design, the use of low quality materials, or employing weak, untried, or even poor technical approaches. In addition, exposure to sudden natural conditions, such as earthquakes, floods, rain, and even very high or very low temperatures, can also be among the major reasons for the failure of construction works worldwide. Recently, particularly following the COVID-19 pandemic, a significant number of collapses, defects, cracks, and poorly constructed field works have been apparent in Kuwait, including the streets in most of the region's states. These have been for a number of reasons, including technical and administrative. The scope and focus of the present study is the field of geotechnical engineering, since improvements to the ground and/or soil layers are considered to be an option for avoiding the failings of poorly-executed works in the field.

Site selection and site investigation is an important issue in the science of civil engineering, particularly in the sphere of geotechnical engineering. Fieldwork is therefore one of the main elements of geotechnical applications in civil engineering. Although it is subject to many different challenges, it provides geotechnical engineers with information regarding the main properties of the site where the proposed project is to be constructed. Weak soil properties can prove to be a significant barrier for certain types of projects where particular specifications are required. For instance, foundations cannot be constructed on weak soil, namely loose soil. Consequently, when the permissible bearing capacity of the soil is less than that deemed to be safe, the soil should be improved using soil improvement techniques, or by employing deep foundations.

This study explores the use of artificial cementation as a soil improvement technique. The effect of using artificial cementation to improve soil properties was investigated by many previous researchers who employed cement in small amounts, mixing it with soil samples [1] [2] [3] [4] [5]. These studies found that the degree of soil cementation particles has significant effects on the cohesion and the angle of the internal friction of the soil, and consequently increases the soil "stiffness" [6]. Moreover, the studies found that the use of artificial cementation for sandy soils reduces the volume, due to the fine cement particles filling the voids between the soil particles [7]. Recently, the use of artificial cementation to enhance soil properties has been employed in Kuwait, for example in transportation projects and slope embankment protection [2] [8]. In particular, soil improvement is necessary for tackling a range of soil problems associated with construction works. For example, for addressing loose soil layers that must be stabilized, or even replaced, in order to create a safe bearing capacity with relatively small deformations [2].

In the current study, a strip footing is considered using a numerical modelling analysis. In general, strip footings are used to support linear loads, such as in the case of walls, and they are suitable for soil with adequate and medium bearing capacity.

Strip footings are also called strip foundations, as their dimensions in both length and width can be considerable; in general, their length is more than twice their width. Strip footings, or strip foundations are an extremely helpful way of tackling the intercausal of isolated footings with small spaces between them. The main role of strip footing, which is classified as a shallow foundation, is to transmit the loads from column loads to the ground [9]. They are commonly employed in low to medium-rise building constructions [10].

This study evaluates the impact of using artificial cementation on the behaviour of soils under strip footings, employing a finite element method, using COMSOL Multiphysics 5.6 software. In total, three main criteria are considered in the exploration of the soil behaviour under the strip footing proposed, namely stress, strain, and displacement. In addition, the soil bearing capacity is considered, in order to evaluate the effect of artificial cementation on the behaviour of the soil. The ultimate bearing capacity is an important indicator of the soil's ability to provide support under the footing proposed. Previous studies evaluated the bearing capacity of different soils [11] [12] [13] [14], using analytical and numerical methods to calculate the relevant bearing capacity. In terms of strip footing, it is generally accepted that the ultimate bearing capacity is one of important issues to be considered in a construction project. Strip footing is usually employed on a semi-infinite, solid bed, and is usually confined by either horizontal or vertical loads [15]. Previous studies used a range of analytical and experimental approaches to compute the relevant bearing capacity [16] [17]. The most common analytical approaches employed were slip line approximation, limit equilibrium analysis, boundary analysis, numerical analysis, and limit analysis, in combination with numerical analysis [18] [19]. In the field of geotechnical engineering, Terzaghi and Meyerhof methods remain those most commonly used [20] [21], although recent advances in technology have encouraged the use of software programs based on the finite element method. The use of the finite element method to solve various geotechnical problems is extremely useful, as a number of previous studies evidenced [22] [23].

The focus of the current study is the assessment of the effect on the strength parameters of soil of using artificial cementation. The study also investigates the soil bearing capacity of the strip footing proposed. In order to obtain accurate results, the Mohr-coulomb constitutive model is employed to study the soil properties and the soil behaviour under the loads applied. This paper discusses the means used to investigate the effect of including Portland cement additives, using a numerical modelling analysis, as well as considering other variable parameters.

2. Methodology

2.1. Materials

The main elements employed in this study were soil samples of sandy soil, and Portland cement. The sandy soil was the same as that collected for a previous study [2]. It was extracted from a depth of 1.0 m to 1.5 m in the Ali Sabah Al-Salem area of the southern part of the state of Kuwait (**Figure 1**). For artificial

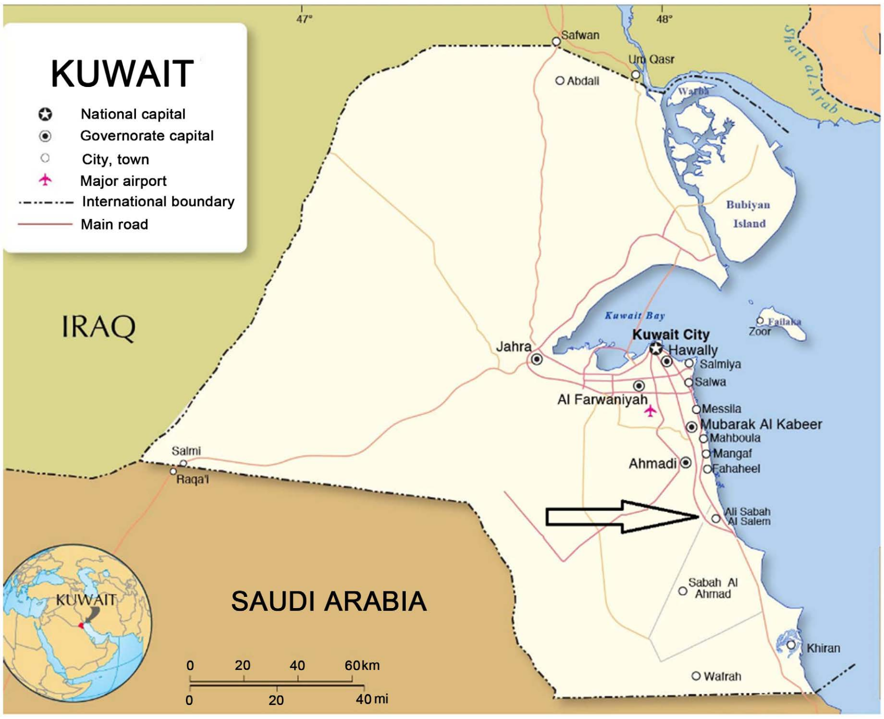

Figure 1. Location of the Ali Sabah Al-Salem area on Kuwait map.

cementation purposes, volumes of 1%, 2%, and 4% weights of Portland cement were added to the sandy soil samples to create artificial cemented sands.

2.2. Testing Programme

The main data required for the numerical analysis study was collected from laboratory tests. Experimental tests were conducted to determine the primary soil properties, such as the water content, specific gravity, liquid limit and, plasticity index. The soil samples collected from the field were prepared in a laboratory, with the optimum moisture content determined using the modified Proctor compaction tests. In addition, strain-controlled, undrained triaxial compression tests were conducted to determine the relevant strength parameters, namely the cohesion, and the angle of the internal friction. The tests were conducted on 21 samples with confining pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa. The data collected from the laboratory experiments and the numerical modelling formed the main part of the study.

2.3. Numerical Modelling

It has recently been determined that implementing the finite element method, using new numerical modelling software, provides a wide range of options and alternative solutions for various different engineering problems and practices. The approach is beneficial for researchers when addressing their research objectives, as it provides an alternative to relying solely on experimental results. For the purpose of the present study, COMSOL Multiphysics 5.6 software was employed to perform the numerical analysis, due to its advanced structural mechanics and stationery physics features. The software enables a wide range of engineering problems to be simulated and analysed. The main objective of this study was to assess the behaviour of the soil under the proposed strip footing numerically, by analysing the results obtained according to stress, strain, and displacement criteria. In addition, the study considered the bearing capacity of the samples. The Mohr-Coulomb constitutive model, a widely-used material model, was employed to model the soil behaviour. The model requires the Young's modulus and Poisson's ratio angle of internal friction and cohesion.

2.3.1. Geometry and Boundary Conditions

A 2-D model was created for the two-dimensional analysis using COMSOL Multiphysics 5.6 software (**Figure 2**). A strip footing with a width of B = 0.6 m was placed on a sandy soil layer. The model dimensions were selected as 3B on the right and 3B on the left side of the footing, and the height of the soil layer was also set at 3B from the base of footing, in order to obtain accurate results in the finite elements analysis. The symmetry feature was applied, in order to reduce the calculation time, and also to obtain more accurate results.

In order to prevent horizontal and vertical movement, a fixed constraint was applied to the bottom of the soil layer, and to prevent the horizontal movement, horizontal constraint roller constraints were applied to the rest of the soil layer.

2.3.2. Material Properties

The objective of this study was to assess the behaviour of the soil under the strip footing proposed by analysing the results obtained according to stress, strain, and displacement criteria, along with considering the bearing capacity. The most suitable approach for assessing the behaviour of the soil was to employ a constitutive model, as the behaviour was non-liner under the loads applied. Therefore, for the purpose of this study, a Mohr-Coulomb constitutive model, a widely-used material model, was employed to model the soil behaviour. As noted previously, the Mohr-Coulomb model requires the Young's modulus and Poisson's ratio angle of internal friction and cohesion. In this study, the modulus of Elasticity and Poisson's ratio used for the soil were 60 MPa and 0.3, respectively.

2.3.3. Loading and Meshing

The main load employed in this study was the foundation load. For the purpose of the analysis, four different boundary loads were applied to simulate the foundation load, namely 1000 kPa, 1500 kPa, 2000 kPa, and 2500 kPa. In order to perform a finite element analysis, the model geometry was discretized into a smaller finite number of elements. Mapped mesh elements were used for the model proposed, with an average element quality of 0.9903. Mapped mesh is constituted of regular rectangles bounded from four sides, with no holes between them [24]. The maximum and minimum mesh size were 0.122 and 4.1×10^{-4}, with a curvature factor of 0.25. The mesh configuration is shown in **Figure 3**.

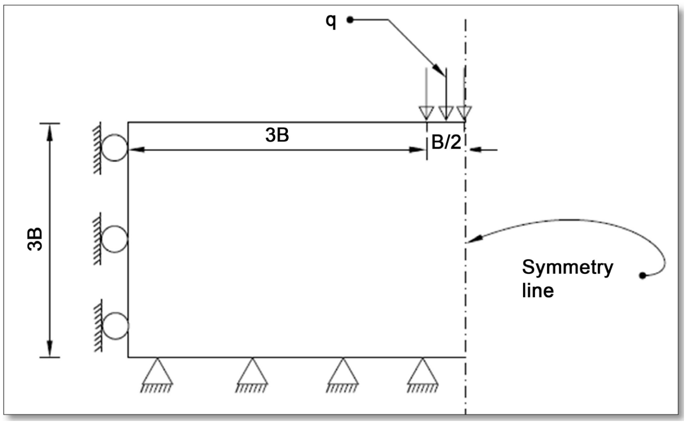

Figure 2. Proposed model.

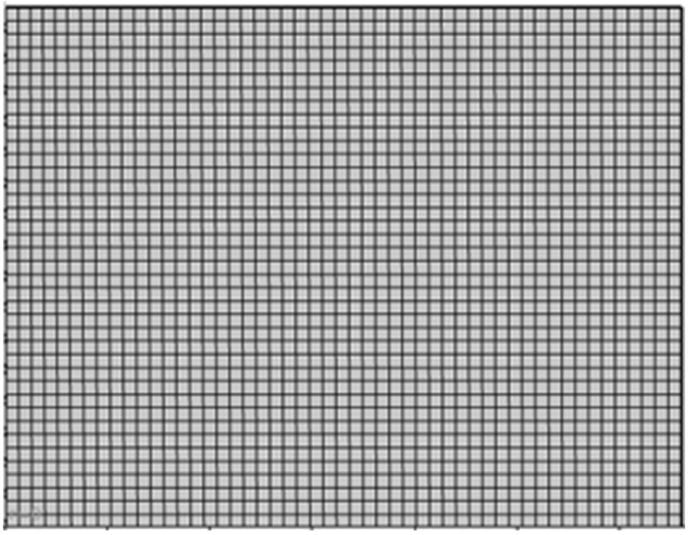

Figure 3. Finite elements mesh.

2.3.4. Model Validation

The validation stage is one of the main elements of any proposed model in numerical modelling applications. In this stage, the appropriate model is identified, and an effective model geometry selected [15]. The triaxial experimental results collated by [2] were validated using the numerical model proposed for this study, and the main experimental results for the drained triaxial tests were simulated. The results of simulation were then compared with the experimental results obtained. After this stage, the model was extended to fulfil the objectives of the study by conducting a more advanced analysis. The model verified and validated by [25], with two different confining pressures, 100 kPa and 200 kPa in the experimental undrained triaxial tests, was that used for the validation purposes. It was found that both the experimental and the numerical modelling had a high consistency and agreement, with small variances ranging between 0.95% and 4.92% (see Figure 4). This fell within an acceptable range in infinite element modelling science.

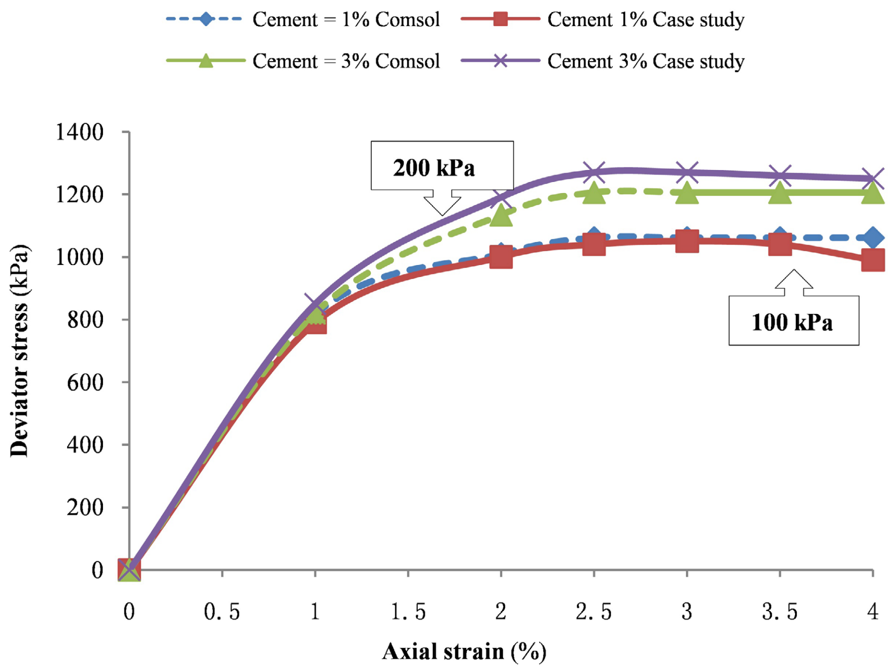

Figure 4. Validation of the proposed model [25].

3. Results and Discussion

The results of this study were determined in two stages, namely the data collected from the experimental tests conducted in the laboratory, and those gathered from numerical analysis conducted by COMSOL Multiphysics 5.6 software. The experimental results obtainedare shown in **Table 1**. It is found that the percentage of the fine particles was 10.2% of the total soil particles, with mean diameter of 0.32 [2]. The soil distribution curve and the soil properties are presented in **Figure 5** and **Table 2**. The soil was classified as SW-SM, namely well-graded sand with silt. The effect on the cohesion of the soil samples of adding different amounts of cement is shown in **Table 1**, which demonstrates that the angle of the internal friction increased by 11.2%, 14.8%, and 17.2% as a result of adding 1%, 2%, and 4% of Portland cement, respectively. The cohesion of the soil also increased from 0 to 60 kN/m^2, 70 kN/m^2, and 165 kN/m^2, when using 1%, 2%, and 4% of Portland cement, respectively. These results indicated that there was a significant effect when using cement to enhance the soil properties.

As stated previously, the numerical model employed by this study was that previously validated by [25]. **Figure 4** illustrates the results of the validation, which had a good agreement between the experimental and numerical results for the different two confining pressures, 100 kPa and 200 kPa. **Table 3** summarizes the results computed from the numerical modelling for the three different cases, 1% cement, 2% cement, and 4% cement, with five different applied loads, 500 kPa, 1000 kPa, 1500 kPa, 2000 kPa, and 2500 kPa. As **Table 3** shows, the effect of using cement in different amounts to create artificial cementation was clear and significant. For instance, in Case 3, with a 2500 kPa applied load, the stresses and

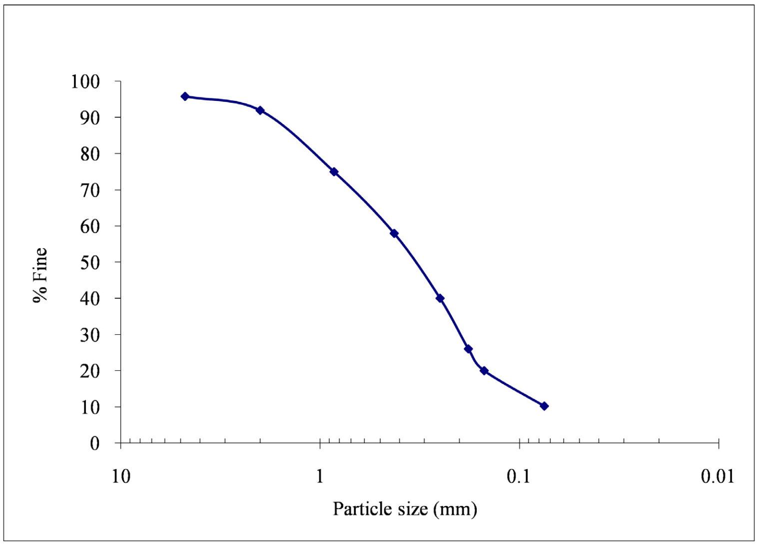

Figure 5. Grain size distribution curve (data collected from [2]).

Table 1. Strength parameters obtained from drained triaxial test (data collected from [2]).

% of Cement	Peak Parameters		Residual parameters	
	Cohesion (kPa)	Angle of internal friction	Cohesion (kPa)	Angle of internal friction
0	0	41.8	0	41.8
1	60	46.5	0	41.8
2	70	48	0	41.5
4	165	49	0	41.5

Table 2. Strength parameters obtained from drained triaxial test (data collected from [2]).

Test type	
Water content	4.10%
Specific gravity	2.68
Liquid Limit	NP
Plasticity Index	NP
C_u	6
C_z	1.185
Unified Soil Classification	SW-SM

strain under the strip footing decreased by 3.24% and 7.42%, and the maximum displacement decreased by 1.47% and 2.97%, as a result of adding cement of 2% and 4%, respectively.

Figures 6-8 shows the maximum stresses, strains, and displacements under the centre of the strip footing, illustrating that the effect of using artificial

Table 3. Results computed from the numerical modelling.

	case 1 (1% Cement)			case 2 (2% Cement)			case 3 (4% Cement)		
q	Max. stress	Max. strain	Max. displacement	Max. stress	Max. strain	Max. displacement	Max. stress	Max. strain	Max. displacement
(kPa)	(kPa)		(mm)	(kPa)		(mm)	(kPa)		(mm)
1000	238.76	0.0034487	8.52	235.57	0.0034027	8.48	235.32	0.003399	8.46
1500	372.34	0.0053782	12.97	361.82	0.0052264	12.84	351.28	0.005074	12.69
2000	511.43	0.0073873	17.53	497.73	0.0071895	17.31	467.06	0.0067464	16.92
25000	657.22	0.0094932	22.18	635.92	0.0091856	21.85	588.72	0.0085037	21.20

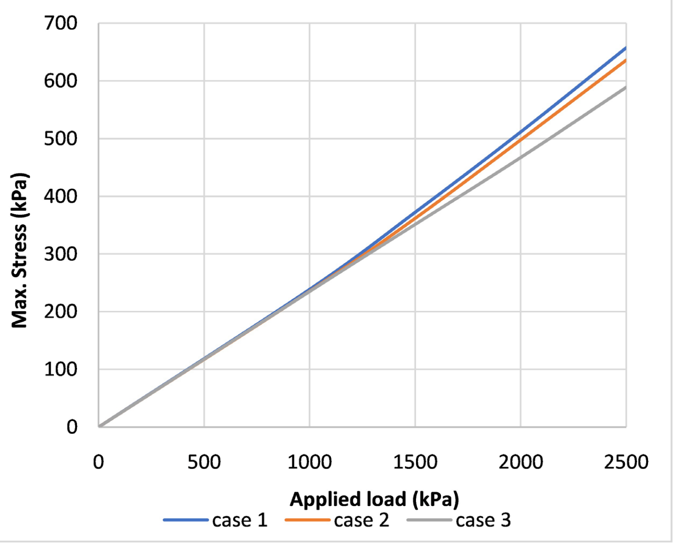

Figure 6. The maximum stress versus applied loads.

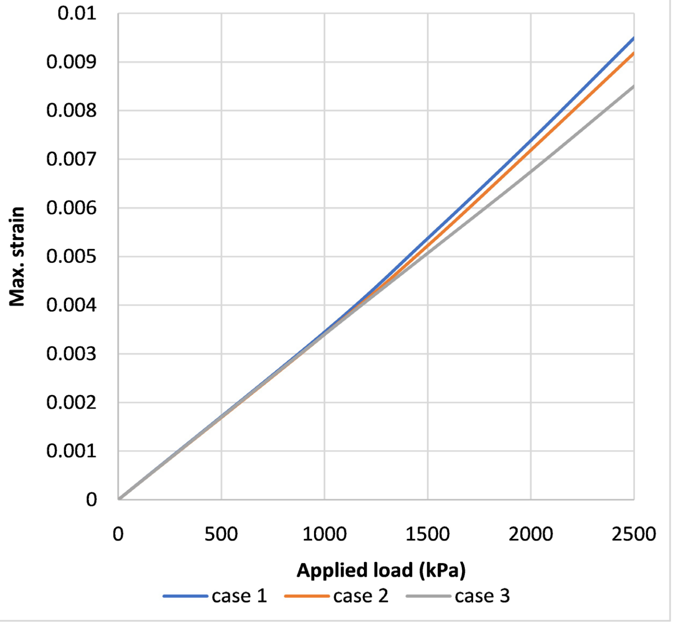

Figure 7. The maximum strain versus applied loads.

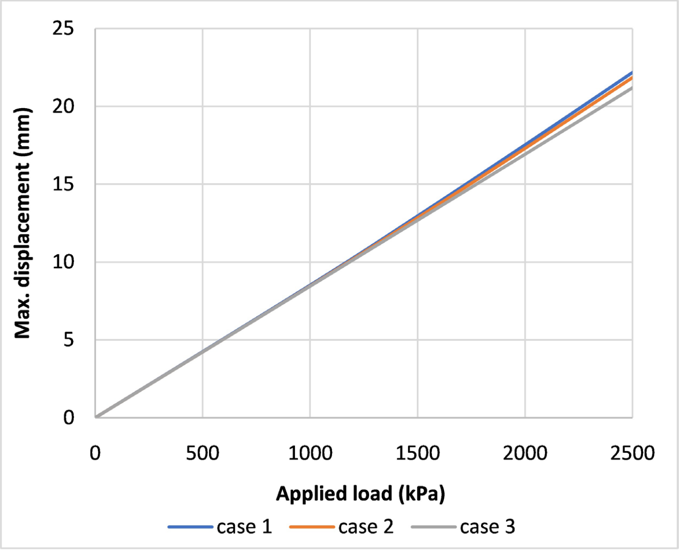

Figure 8. The maximum displacement versus applied loads.

cementation was significant in the cases where the high loads were transmitted from the footing, such as in the 2500 kPa load. In other words, high resistance was evident when reducing the stresses, strains, and displacements by the respective amounts employed in this study. This can be attributed to the fact that the increase in the cementation bond between the soil particles engendered an increase in the strength parameters, namely the cohesion and the angle of internal friction. In addition to the induced cementation, namely the artificial cementation, the increase in the fine particles from the added cement filled the voids in the soil skeleton, causing an increase in the unit weight, and therefore an increase in the cohesion between the soil particles.

The increase in the strength parameters, namely the cohesion and angle of internal friction, also had a significant effect on the soil resistance under the strip footing, increasing the bearing capacity of the soil bearing capacity significantly. **Table 4** shows the bearing capacity values for the three cases, Case 1 (1% cement), Case 2 (2% cement), and Case 3 (4% cement), demonstrating that the bearing capacity of the soil under the strip footing proposed increased significantly. This increase in bearing capacity value was expected, and can be attributed to the increase of the bearing capacity factors as a result of increasing the amount of the cohesion and the angle of the internal friction. **Figures 9-11** show the failure under the strip footing model proposed for the three cases, illustrating the failure mechanism for the three scenarios at a 2500 kPa load. It should be noted that embedment depth of the strip footing was ignored for the purpose of simplicity. As shown in Figures, normal and symmetric failure occurs with lateral extension towards the centre of the footing. It should be noted that the type of mesh used in the numerical modelling analysis had a significant effect on the resulting failure mechanism under the strip footing. Thus, in the mesh selection stage of this study, a finer size of map mesh was considered.

Table 4. Bearing capacity under the strip footing (kPa).

	Cohesion (kPa)	Angle of internal friction	Bearing capacity (kPa)
No cement	0	41.8°	816.64
case 1	60	46.5°	11730.36
case 2	70	48°	16647.14
case 3	165	49°	40124.01

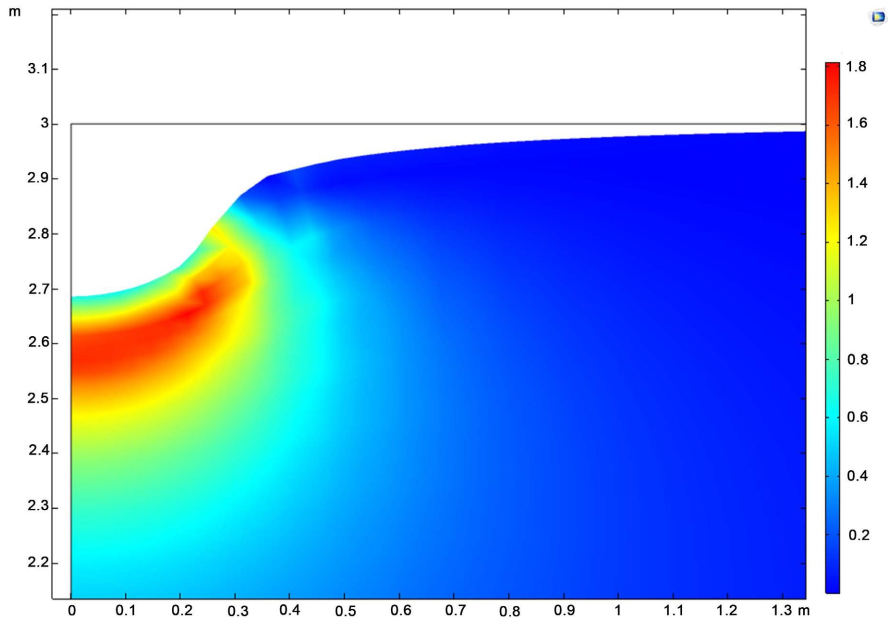

Figure 9. Failure of the soil under the strip footing for case 1.

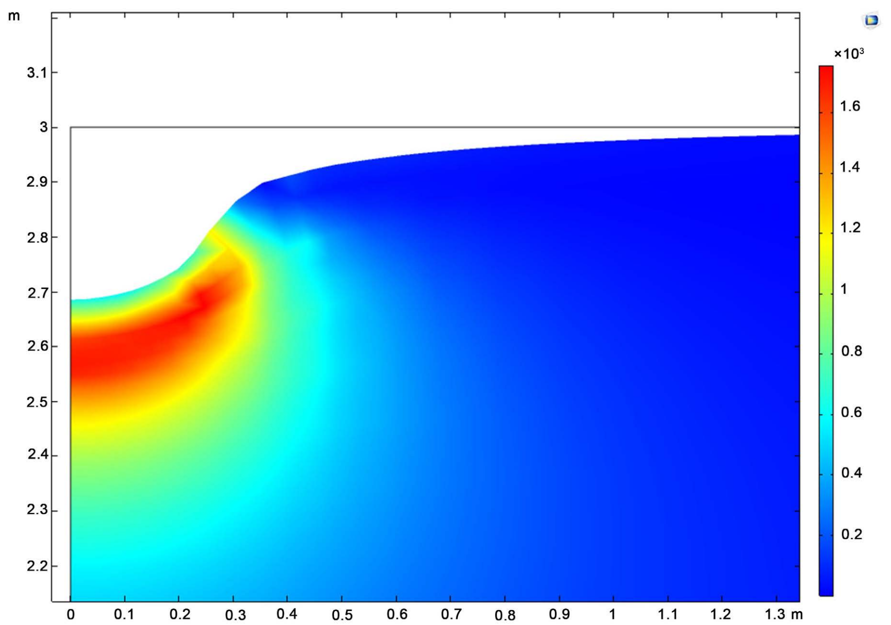

Figure 10. Failure of the soil under the strip footing for case 2.

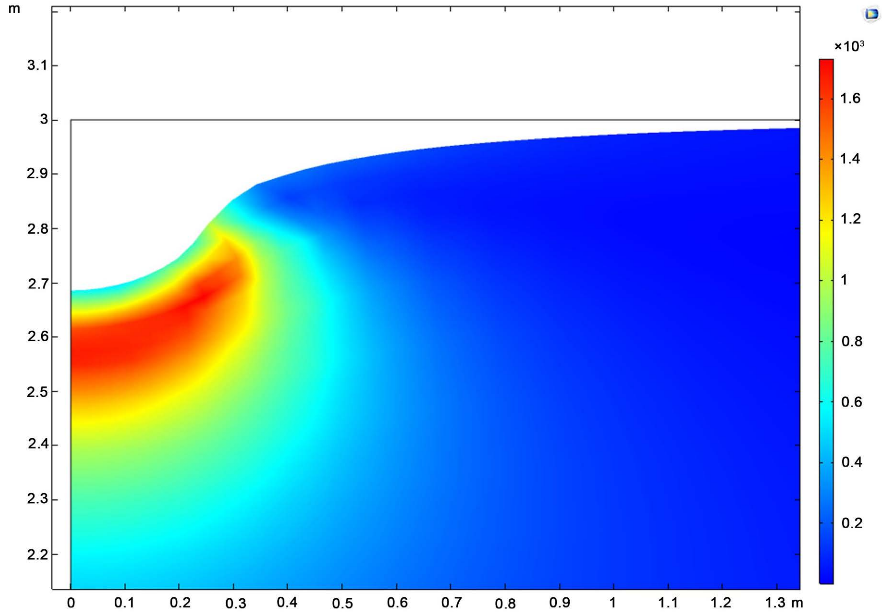

Figure 11. Failure of the soil under the strip footing for case 3.

In addition to the results from the numerical analysis, the bearing capacity, which is one of the main design criteria for foundations, was determined. The results obtained are shown in **Table 4**, demonstrating that the effect of artificial cementation was significant, especially for the cases in which the amount of cement added was 2% and 4%. These significant results can be attributed to the increase in the soil strength parameters, namely the cohesion and the angle of internal friction, as these factors constituted the main input of the bearing capacity equation. From an economic stance, the use of 2% cement is recommended as the best option, as strip footings are not generally required to support high loads. In addition, as shown in **Figures 6-8**, the behaviour of the soil under the strip footings proposed for 500 kPa, 1000 kPa, and 2000 kPa behaved in similar manner across the three different scenarios when the investigative elements of this study were applied, namely the maximum stresses, strains, and displacements. The effect of adding different amounts of cement was also examined, in terms of the plastic strain. **Figures 12-14** illustrates the plastic regions for the different cases at 2500 kPa, showing that that adding the specific amounts of cement to the soil reduced the plastic regions around the expected failure areas in the soil layer significantly. It should be noted that the results obtained, computed via the numerical analysis that employed the finite element method, were based on the data obtained in the experimental study conducted by [2], following the verification and the validation of the proposed model. This allowed the authors of the present study to examine the influence of artificial cementation on the soil layer under the strip footing proposed. In addition, it should be noted that the scope of this study to investigate other factors or properties was limited by the availability of data. It is therefore recommended that future studies investigate the effects of other parameters, such as soil consolidation parameters.

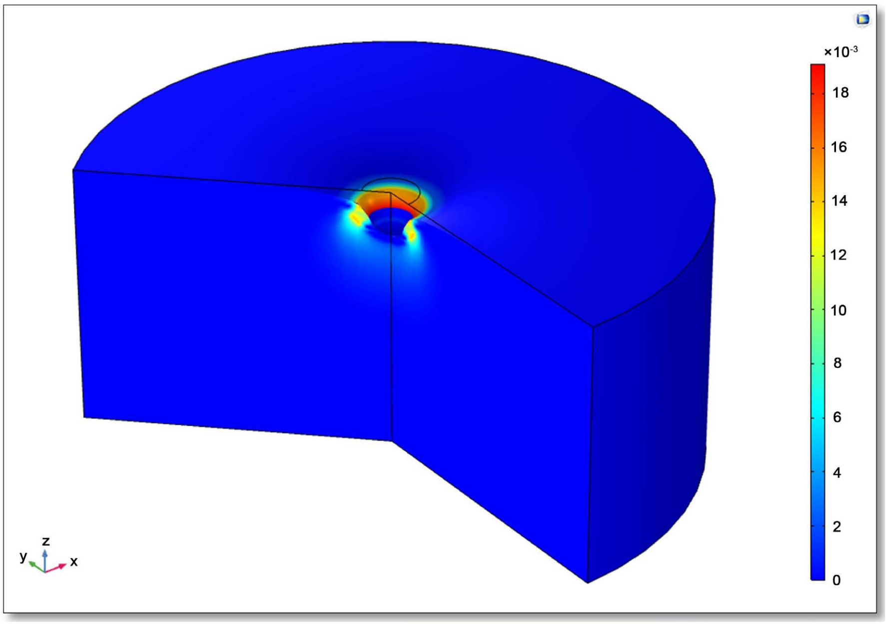

Figure 12. Plastic regions under the strip footing for case 1.

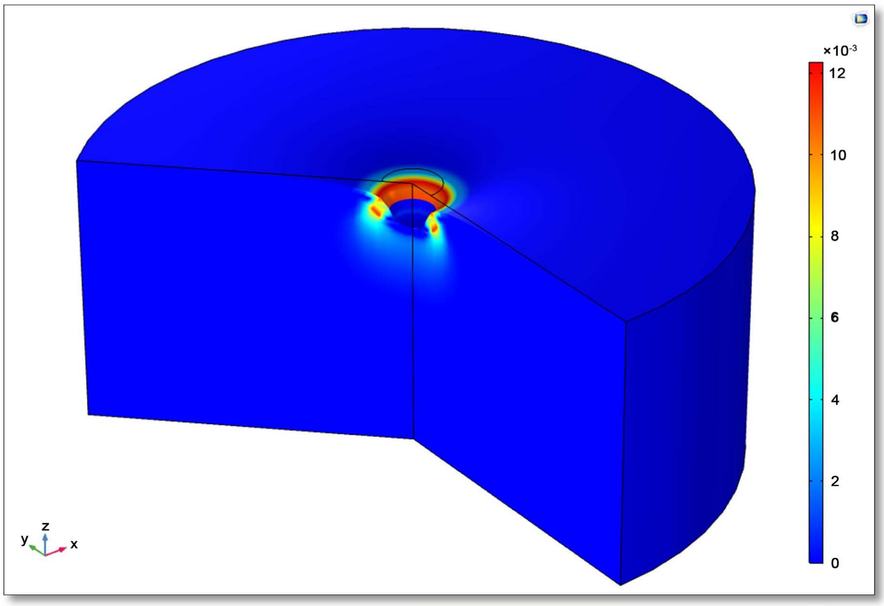

Figure 13. Plastic regions under the strip footing for case 2.

4. Conclusions

1) In order to investigate the influence of using artificial cementation on the behaviour of sandy soil under strip footing in Kuwait, comprehensive laboratory tests were conducted on soil samples from the Ali Sabah Al-Salem area. Numerical modelling was performed to study the behaviour of the soil under the strip footing proposed, in terms of stress, strain, and displacement criteria. In addition, bearing capacity criteria were also considered. Based on the laboratory and field test results, it was possible to conclude and recommend the following:

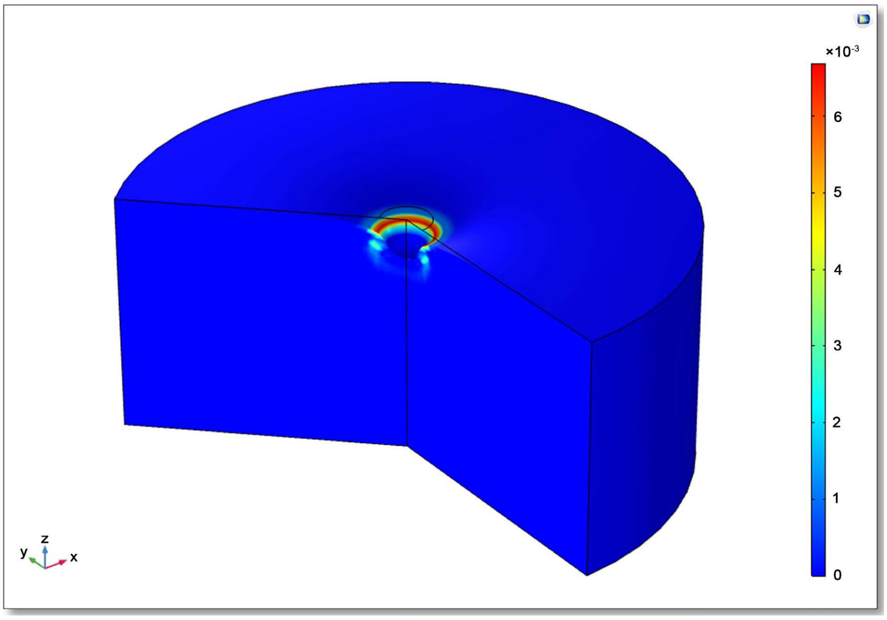

Figure 14. Plastic regions under the strip footing for case 3.

2) Adding different amounts of cement to the soil samples in the study had a significant effect on the soil strength parameters, namely the cohesion and the angle of internal friction;

3) The angle of internal friction increased by 11.2%, 14.8%, and 17.2%, as a result of adding 1%, 2%, and 4% of Portland cement, respectively;

4) The cohesion of the soil increased from 0 to 60 kN/m^2, 70 kN/m^2, and 165 kN/m^2 for 1%, 2%, and 4% of Portland cement, respectively;

5) The stresses and strains under the strip footing proposed decreased by 3.24% and 7.42%, and the maximum displacement under the proposed model decreased by 1.47% and 2.97%, as a result of adding cement of 2% and 4%, respectively;

6) The bearing capacity values of the soil under the strip footing proposed increased by a significant amount, which can be attributed to the increase in the bearing capacity factors;

7) This study recommends that future studies might investigate, for example, the plastic strain of soil around the strip footing, and investigate other soil parameters, such as soil consolidation parameters.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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