Behaviour of Foundation Rested on Finite Saturated Salt-Encrusted Flat Soil (Sabkha) Improved by Cement Addition under Repeated Loading

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ABSTRACT: The dynamic response of a block machine foundation rested on the finite thickness of cemented sabkha was investigated by carrying out a 1g small scale test. The parameters that were considered in the account in the study were cement content, ratio of thickness of the cemented sabkha to the foundation's diameter, magnitude and rate of pulse load. The results revealed that the cement content has a significant effect more than the thickness of cement-sabkha. The reduction in the maximum settlement value by increasing cement content decreases with the increased thickness of cement-sabkha. The rate of pulse loading leads to an increase in the maximum settlement of at least 100 and 60% for thickness ratios of 0.2 and 0.4, respectively, and these effects decrease with the increasing thickness of cement sabkha. The influence of the value pulse loading and the rate of the pulse loading on the raising of the sabkha's stresses increases with increasing thickness ratio more than cement content. In terms of the liquefaction risk of the sabkha soil that underlies the cement-sabkha layer, there is no liquefaction in sabkha soil when the value and rate of pulse loading that is applied to the foundation are less than 240 N and 200 blows/min. The maximum pore pressure ratio (r_u) value ranges from 0.07 to 0.1.

KEYWORDS: Pore pressure, settlement, cement, thickness, stress.

1. INTRODUCTION

The structure-soil interaction of a shallow foundation under repeated loading was studied in different subsoil conditions. Islam and Gnanendran (2014) studied the performance of a foundation that rested on a sloped granular fill under repeated loading. Pasten et al. (2014) studied the influence of repetitive loading on the long-term behavior of geosystems by capturing the volumetric and shear strain of the subsoil generated due to repeated loading. Tafreshi and Dawson (2015) studied the response of square footing that rested on subsoil reinforced by single or multilayer geocell under repeated loading. Mehrpazhouh et al. (2019) investigated the behaviour of unreinforced and reinforced sand with nonwoven geotextile using repeated CBR loading tests (followed by unloading and reloading). Tafreshi et al. (2011) investigated experimentally, and numerically the influence of incremental cyclic loading on the response of a circular footing rested on the sand. Fattah et al. (2017) studied the cyclic behavior of footing on dry sand under several loading rates. Hegde and Sitharam (2016) studied the cyclic behaviour of plate loading rested on unreinforced/or reinforced clay by geocell and geogrid. Based on the previous studies, the generation of excess pore pressure and stresses in the soil profile that developed throughout the repeating loading operation was not considered in the response of the structure-soil interaction.

Sabkha is a salt-encrusted flat area that has a high salt content. Sabkha covers most areas of the coastal Arabian Gulf, North Africa, and some areas of Australia, where there are several industrial activities and rapid development in that area. The soil is hard in dry conditions and loses strength due to wetting. Sabkha soil is problematic soil and has potential liquefaction. Therefore, sabkha must be improved by either mechanical method such as Vibro compaction, replacement compaction, and preloading (Akili, 2004; Juillie and Sherwood, 1983; Dhowian, 2017), chemical stabilization such as stabilized by cement (Aiban and Ali, 2001; Al-Amoudi, 2002; Mohamedzein and Al-Rawas, 2011; Stipho, 1989), stabilized by gravel with cement (Abbas, 2012), stabilized by lime and asphalt cement kiln dust (Al-Amoudi, 1994; Asi, 2001; Al-Homidy et al., 2017; Nasr, 2015), or stabilized by geosynthetic, (Aiban et al., 1998). Al-Amoudi (2002) stated that cement could mix with sabkha at its natural water content (18-23%), and their strength was close to the strength of cement-sabkha that compacted at OMC. Therefore, the type of improvement for sabkha used in this paper is cement stabilization (cement-sabkha).

On the other hand, there is limited research dealing with structure-sabkha interaction. Alnuaim and El Naggar (2013, 2014) have investigated the structure-sabkha interaction of deep foundation under static load. Furthermore, the potential liquefaction of sabkha under dynamic loading was studied by Ahmed and Al Shayea (2017) and Alnuaim et al. (2021).

Based on the literature, there is a lack of information on dynamic structure-sabkha interaction. Dynamic forces can excite machine foundations due to reciprocating, rotating, and impulsive actions (impact machine). Reciprocating and rotating machines, such as diesel generators, gas turbines, centrifugal compressors, and electrical motors are subjected to steady-state harmonic, dynamic actions. Whereas impulsive machines, such as forging hammers and metal forming presses, are subjected to sudden pulse force. This paper will be limited to impact machines.

The behaviour of foundations rested on a finite thickness of cement-sabkha and subjected to repeated loading was experimentally investigated using a 1g small scale test. The cement content added to sabkha was 5 and 10 %. The thickness ratio, which is defined as the thickness of cemented sabkha to the foundation's diameter, was changed to 0.2 and 0.4. The foundation was subjected to vertical repeated loading, with a magnitude of 80, 160, and 240 N, as well as the frequencies of 200, 50, and 20 blows/min. A block foundation was used with a diameter of 5 cm. The results were considered in terms of displacement of foundation, pore pressure, and stress of the sabkha profile underneath the cemented sabkha layer to investigate their liquefaction potential.

2. MATERIALS

Three soils were used in this paper: natural sabkha soil, cement-sabkha with 5 and 10% cement content. The natural sabkha soil was collected from the Ras-Al Ghar area, Eastern Region, Saudi Arabia. The sabkha loses its strength by wetting; the sources of the wetting are rainfall or rising groundwater tables. Therefore, the condition of sabkha used in the physical model is saturated by sabkha brine. The primary properties of the collected sabkha are shown in Table 1. The results of X-ray diffraction (XRD) test reveal that the main minerals that were found in sabkha were dolomite, calcite, and gypsum (Alnuaim et al. (2021)).

3. PREPARATION CEMENTED SABKHA

In the field, the region of sabkha that can be improved by cement addition is limited. Therefore, the subsoil of cemented sabkha used in the physical model had finite dimensions. Because the foundation's cross-section is circular, the shape of cemented sabkha is a cylinder inserted into sabkha soil. In the paper, the diameter of the cemented sabkha was two times the foundation diameter.

Table 1 Properties and classification of the sabkha soil (Alnuaim et al. (2021)).

Property	**Value**
Specific gravity Gs	2.78
Dry unit weight γ_d (kN/m^3)	15.01
Water content (%)	23
Passing through # 200 (%)	27.74
D_{10} (mm)	0.02
D_{30} (mm)	0.09
D_{60} (mm)	0.21
Cu	11.39
Cc	2.20
USCS Soil type	SM
AASHTO soil type	A-3

For the preparation of cemented sabkha, the used cement was ordinary Portland cement (OPC) with a specific gravity of 3.15. The cement was first added and mixed with 3 kg of dry sabkha soil during the compaction test process. Then, an amount of distilled water (3% of the weight of soil + added cement) was added and mixed, where the water reacts with cement and generates gel surrounding the particle soil, causing the mixture to become hard. After that, the standard compaction test was completed (Rock, 2007). An unconfined compressive strength test with a loading rate of 0.5 mm/min was carried out to determine the strength of the cemented sabkha sample with two cement contents. The sample sizes used were 50 and 100 mm in diameter and height, respectively. It should be noted that the samples were cured by placing them in a desiccator for 28 days before the testing. The characteristics of cement-sabkha of 5% and 10% of cement content are shown in Table 2.

Table 2 Properties and classification of the cement-sabkha of cement percentage of 5%

Property	**Cement content**		**Reference**
	5%	10%	
$\gamma_{d\text{-}max}$ **(kN/m3)**	17.01	18	(Rock, 2007)
OMC	15	14.9	
c_u **(kN/m^2)**	780	3000	(ASTM, 2003)

4. PHYSICAL MODEL

4.1 Machine Foundation Model

The main objective of any modelling is to obtain an optimal cost-effective, safe design (Springman, 2007). There are several modeling methods, such as the full-scale model, centrifuge model (n.g), and small-scale model (1g). Adopting small-scale models has a great advantage: they have full control over all the details of the model and the geotechnical properties of the soil used in the tests. In addition, a small quantity of the soil, a small container, small lengths of the foundation, and a short period are required to implement the test compared with those requirements in full-scale (prototype). However, tests on small-scale models fail to model the soil's effective stresses because stresses are not correct and since soil behaviour is nonlinear (Wood, 2003). On the other hand, small-scale tests show the general trend of the model's behavior.

There are several machines, such as rotary machines, reciprocating machines, and impact machines. Several types of impact machines are used by the industry, where the repeated impact loading is generated by frog hammers, drop hammers, and drop crushing, while the impulse/pulse loading is generated by drop crushers, pig breakers, jolters, forging and stamping presses, etc. (Bhatia, 2008). The type of machine considered in this paper is an impact machine due to the high value of the dynamic forces subjected to the foundation.

The machine foundation depends on the type and characteristics of a machine. In general, machine foundations are block, top frame, and pile foundations. In addition, the most commonly used foundations in the industry are block foundations and frame foundations (Bhatia, 2008). The minimum thickness of the block foundation is 0.6 m to ensure the foundation's behavior as a rigid body with six degrees of freedom. In addition, the foundation thickness of the impact machine may reach 3 m. In this paper, the type of machine foundation is a block foundation.

The dimension of the block machine foundation prototype was obtained from the rotary machine that was given in the reference (Arya et al., 1979). The length, width, and prototype thickness were 6.25, 3.125, and 0.75 m, respectively. The foundation shape was converted to a circular shape with an equivalent diameter ($D_{eq} = \sqrt{(4B.L/\pi)}$), where B and L are the breadth and length of the prototype, respectively. It should be noted that the reciprocating machine was an example of the foundation. Hence, the foundation's thickness was adjusted to suit the impact machine. The scale length factor, the prototype dimension, and the dimensions of the corresponding model are shown in Table 3.

Table 3 Characteristics of prototype and model foundation

Foundation	**Prototype**	**Model**
Length scale factor (n_L)	100	
Diameter	5 m	5 (cm)
Thickness	2 m	2 cm
Material	Concrete	Aluminium

4.2 Loading System

The loading system consists of air-powered testing apparatus (control box and actuator unit), chamber, frame load, transducer measurement tools, and data acquisition.

4.2.1 Air-powered Testing Apparatus

An air-powered testing apparatus is used to compute the resilience modulus used in designing the pavement. The device used in the study is to generate the static and repeated loading modes on the foundation model. It consists of a control cabinet and an actuator unit. Static and repeated load, electrical signals to the Mac valve (valve controls the period of repeated loading) are monitored from the control cabinet. Figure 1(c) shows the electro-pneumatic system used to apply loads. The actuator unit consists of an air cylinder, a shuttle valve, a pilot air supply, the main air supply, and a mac valve, which requires a 110-volt power supply. The air cylinder can be activated either by the mac valve or the static load line. The shuttle valve regulates airflow to the air cylinder. The shuttle valve closes the static load line when the mac valve is activated. In other words, a dual timer controls the electrical signal to the mac valve and counts the number and duration of load pulses. In addition, there are on-off switches and fatigue-modulus switches in the cabinet control. The modulus switch activates the timer, counter, and dynamic load.

4.3 Container of Soil

To eliminate the influence of wall side friction, the ratio of the diameter to the length of the container should be equal to or more than one. Therefore, the ratio of height to the diameter of the container in this paper is 0.85. In terms of reducing the effect of boundary conditions, the container's diameter is eight times that of the foundation model. The nature of the loading applied to the machine foundation model is static and repeated loading. Therefore, the stress waves propagate throughout the filled sabkha and reach the chamber wall, reflecting them into the model. The reflected waves may cause some disturbance to the measurements of vibration and deformations. A cork sheet with a thickness of 2 cm was placed between the vertical wall and the sabkha soil to minimize the reflected waves. In addition, a cork sheet can reduce the slight friction that might be developed between the box faces and soil. To examine the efficiency of the crock sheet in absorbing the waves generated from the foundation, the vibration amplitude was measured at the boundary of the chamber during repeated loading. It was found that a minimal deformation was recorded equal to 1.9 µm, which is a negligible value.

In order to consider the scale effect of the test soil, Vipulanandan et al. (1989) stated that it is desirable to keep the ratio between the diameter of the foundation and the effective-soil particle-size diameter (D_{10}) at a value of 50 or greater to minimize internal scale effects between a penetrating object and the test soil. In their study, they used a ratio of 100. The D_{50} of test soil is 0.15 mm, and the ratio of the foundation's width to mean particle size is greater than 300.

4.4 Drainage System

The sabkha was filled into the chamber by six layers, where the density of each layer was natural density (15.01 kN/m^3). Then, the sabkha was saturated, and the type of fluid was sabkha brine. The saturation was carried out using a flow net lying at the bottom of the chamber. As a result, the sabkha brine flows through the sabkha from down to up under a small elevation head to ensure a laminar flow, which aids in the escape of air from sabkha voids. It should be noted that the shape of the flow net is symmetrical to ensure the homogenous saturation of sabkha.

4.5 Frame Loading

The steel frame loading consists of four columns and six main transverse beams, in which four beams fasten the four columns peripherally at the bottom, and another two beams fasten the columns at the top. The secondary transverse beam was welded to the two top main beams. Four base plates with a size of 400 x 400 x 8 mm were welded at the bottom of the column. It should be noted that the column and beam section are channel sections with a web length of 200 mm, a flange length of 75 mm, and a thickness of 10 mm. The actuator that produced static and repeated loads was placed at the mid-span of the secondary transfer beam, where a suitable opening was made in the mid of the beam to pass the rod of the actuator applied to the foundation model.

4.6 Instrumentations

To measure the settlement, two LVDTs with a capacity of 10 mm each were installed at the top of the foundation model to measure the settlement. To record the induced stress at sabkha soil for several levels during repeated loading, three stress transducers (PDA-PB) of capacity and weight of 100 kPa, and 0.7 grams each were used in the model. The transducers are waterproof for ordinary daily use. It should be noted that the liquid used in the physical model is sabkha brine, which has a high concentration of dissolved salt. Al-Amoudi and Abduljauwad (1995) pointed out that the salt concentration of sabkha brine typically ranges from four to five present in the seawater. The stress transducers and pore pressure gauge were enveloped by a piece of nylon. In addition, three small pore pressure gauges with a capacity of 200 kPa were used for each test. The pore pressure gauges use a silicone diaphragm as a differential pressure-sensitive element. A porous stone is provided to separate the diaphragm from the soil. A piece of filter paper was placed on the porous stone to prevent the clogging of the pones of porous stone from a soil particle during the test. As in any piezometer, this porous stone must be saturated before use and kept saturated during testing.

Based on the specification of the transducers, the dynamic loading has an adverse influence on the function of the transducer. Therefore, to minimize the adverse effects of dynamic load on the function of transducers, the stress transducers and pore pressure gauge were installed at the foundation's edge model at several elevations. It should be noted that the pore pressure gauges and stress transducers were installed in saturation sabkha soil underneath the cemented sabkha layer, as shown in Figure 1(b).

5. Test Procedure

The parameter studies that were considered in this paper were cement content (5 and 10%), the thickness ratio of cemented sabkha (0.2 and 0.4), repeated loading values (80, 160, and 240 N), and the rate of speed of repeated loading (200, 50, and 20 blows/min). Therefore, 36 models were carried out, as shown in Table 4.

Table 4 Configuration tests

Model's Name	**Cement content (%)**	**Thickness ratio**	**Pulse loading (N)**	**Loading speed (blows/min)**
Model-1	5	0.2	80	200
Model-2	5	0.2	80	50
Model-3	5	0.2	80	20
Model-4	5	0.2	160	200
Model-5	5	0.2	160	50
Model-6	5	0.2	160	20
Model-7	5	0.2	240	200
Model-8	5	0.2	240	50
Model-9	5	0.2	240	20
Model-10	5	0.4	80	200
Model-11	5	0.4	80	50
Model-12	5	0.4	80	20
Model-13	5	0.4	160	200
Model-14	5	0.4	160	50
Model-15	5	0.4	160	20
Model-16	5	0.4	240	200
Model-17	5	0.4	240	50
Model-18	5	0.4	240	20
Model-19	10	0.2	80	200
Model-20	10	0.2	80	50
Model-21	10	0.2	80	20
Model-22	10	0.2	160	200
Model-23	10	0.2	160	50
Model-24	10	0.2	160	20
Model-25	10	0.2	240	200
Model-26	10	0.2	240	50
Model-27	10	0.2	240	20
Model-28	10	0.4	80	200
Model-29	10	0.4	80	50
Model-30	10	0.4	80	20
Model-31	10	0.4	160	200
Model-32	10	0.4	160	50
Model-33	10	0.4	160	20
Model-34	10	0.4	240	200
Model-35	10	0.4	240	50
Model-36	10	0.4	240	20
Model-37	-	-	80	200
Model-38	-	-	80	50
Model-39	-	-	80	20
Model-40	-	-	160	200
Model-41	-	-	160	50
Model-42	-	-	160	20
Model-43	-	-	240	200
Model-44	-	-	240	50
Model-45	-	-	240	20

For each model, the dry natural sabkha was first placed in the chamber in the six-layer; during the preparation of natural sabkha in the chamber, pore pressure gauges and the stress transducers were placed at specified depths of-2.0, -5.0, and -10.0 cm. Then, the saturation processes were initiated by flowing sabkha brine through a flow network installed at the bottom of the chamber; the direction of sabkha brine flow is from down to up. This process ensures that the air from the sabkha soil is repelled and assists in the saturation of the sabkha. After that, when the soil was submerged for 24 hours, the cemented sabkha cylinder was inserted at the centre of the top surface of the submerged sabkha. Then, the foundation model was placed centrally over the surface of the cemented sabkha. Then, the loading rod of the actuator unit was mounted just at the centre of the soil stress transducer to prevent eccentric loading. Two LVDTs were installed on the top of the model, as well as Then a small static load of 40 N was applied to the model; the tests were carried out by applying a given value and rate of repeated loading for two minutes. The data logger recorded the measurements of settlement, stress, and pore pressure.

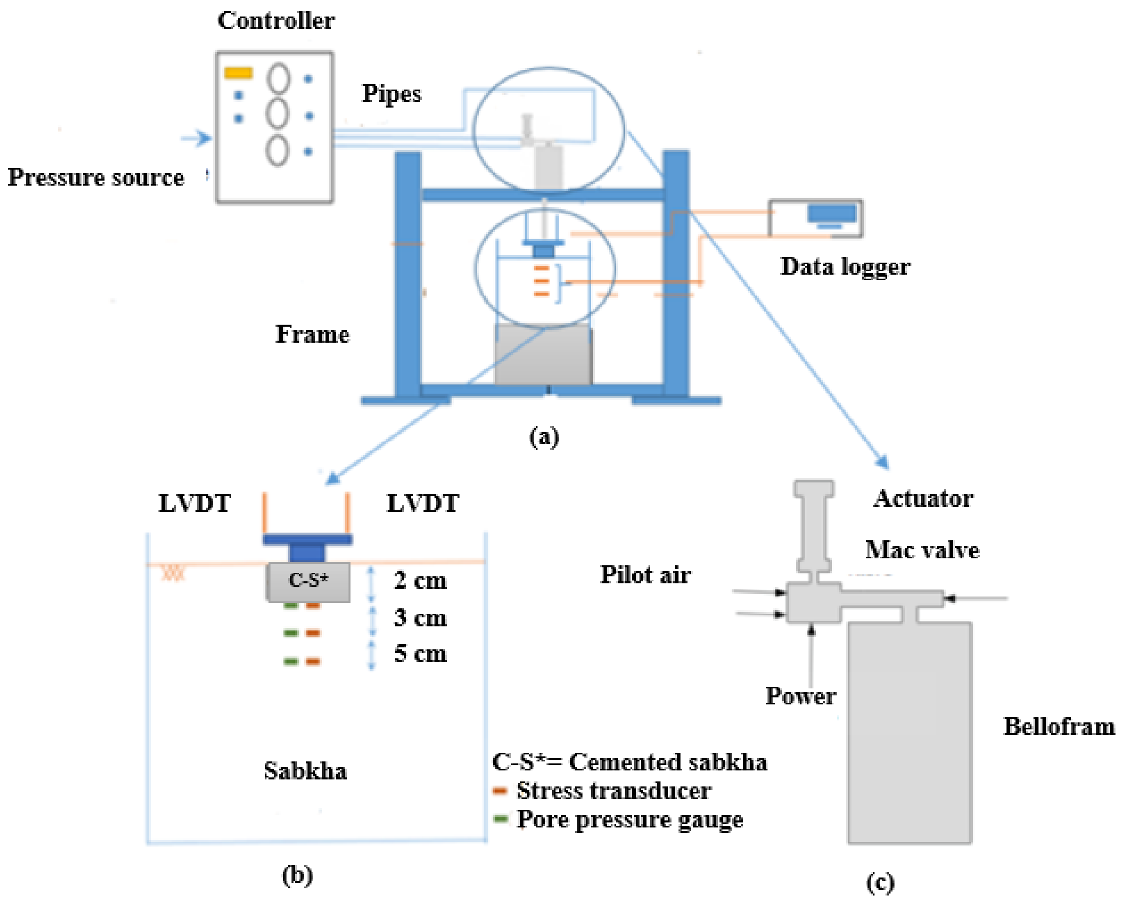


Figure 1 (a) Test setup, (b) foundation model, cemented sabkha, pore pressure gauges, stress transducers, two LVDT configuration, and (c) Actuator unit

6. Results and Discussions

The behavior of foundation deformation can be categorized into two groups: The first group's settlement continues to increase with time. The increasing rate of settlement decreases with time. As shown in Figure 1, the deformation initially increases with time and reaches a constant value. The maximum settlement at the end time for the first group or a constant value of a settlement in the second group was considered. The settlement increases with increasing speed and value of repeated loading and decreases with increasing cement content and thickness ratio. Figures 3(a) and 2(b) show the maximum settlement versus percent of cement for several rates of pulse loading (200, 50, and 20 blows/min) at a thickness ratio of cement-sabkha of 0.2 and 0.4, respectively. The rate of pulse loading leads to an increase in the maximum settlement of at least 100 and 60% for thickness ratios of 0.2 and 0.4, respectively. With increasing cement percentage, the effect of pulse loading rate significant on the maximum settlement decreases. In addition, the influence of the rate of pulse loading on the maximum settlement decreases with the increasing thickness of cement-sabkha. The reduction in the maximum settlement value by an increase in cement percent decreases with the increasing thickness of cement-sabkha. For example, at a rate of 200 blows per min, the maximum settlement at a percent of cement of 5 and 10% are 3.5 and 2.9 mm, respectively, at the thickness of cement-sabkha of 1 cm, while the maximum settlement at a percent of cement of 5, and 10% is 1.6 and 1.3 mm, respectively, at the thickness of cemented sabkha of 2 cm. On the other hand, at a given level of cement content, the rate of pulse loading has a significant effect on the settlement of the model foundation. These effects decrease with the increasing thickness of cemented sabkha.

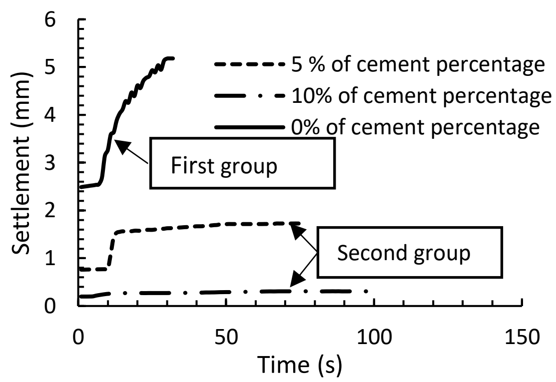


Figure 2 Settlement-time history at Pulse loading = 80 N, and rate of loading = 200 blows/min for several percent of cement

Figures 3(c) and 3(d) show the maximum settlement versus cement content for several values of pulse loading (80, 160, and 240 N) at a thickness of cemented sabkha of 1 and 2 cm, respectively. Like the influence of the rate of pulse loading, the influence of the value of repeated loading on the maximum settlement decreases with the increasing thickness of cemented sabkha. Unlike the effect of the rate of pulse loading, at a given cement content, the value of pulse loading has an insignificant effect on the settlement of model foundations, as shown in Figures 2(c) and 2(d).

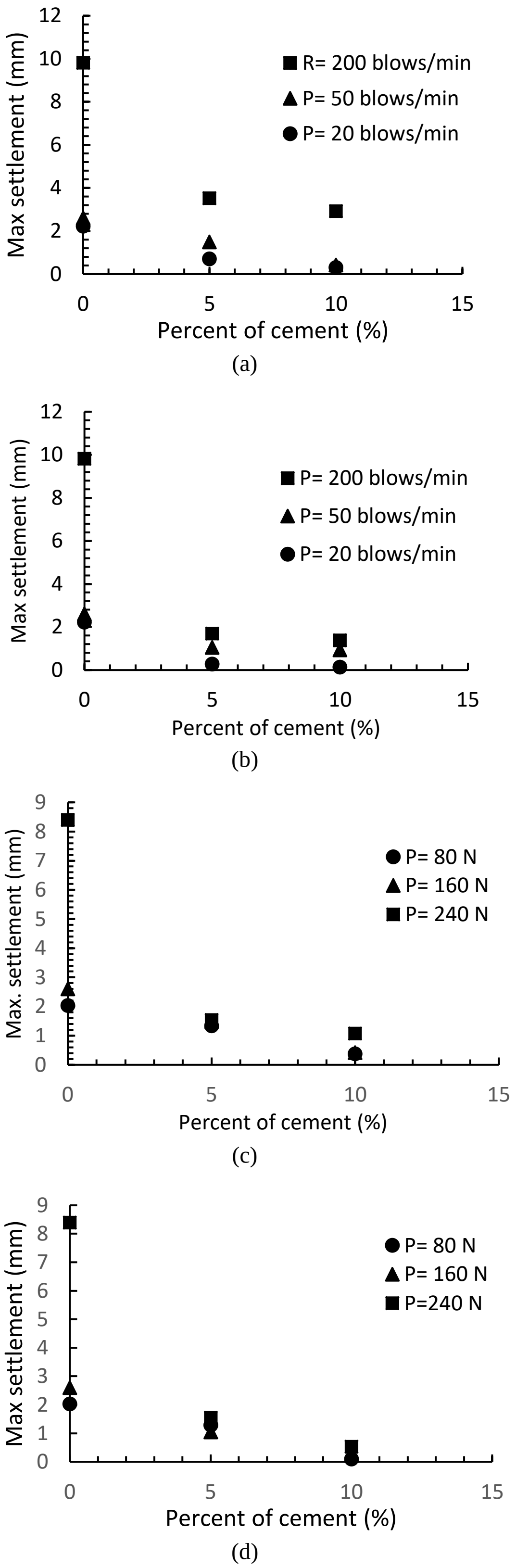


Figure 3 Maximum settlement of foundation versus percent of cement for several rates of the pulse at a thickness of cement sabkha at pulse loading of 160 N: (a) 1 cm, (b) 2 cm, and for several of value of pulse loading at thickness of cement sabkha and rate of pulse loading of 50 blows/min, (c) 1 cm, and (d) 2 cm

To investigate the liquefaction initiation in the sabkha soil underneath the cemented sabkha layer during repeated loading, the stresses and pore pressures at the different depths of the sabkha were examined. The permeability of its undisturbed specimens ranged from 1.24 x 10^{-6} to 3.2 x 10^{-5} m/s (Al-Amoudi and Abduljauwad, 1995). Figures 4(a) and 4(b) show the change in stresses and pore pressures with time for different depths (2, 5, and 10 cm from the ground surface, respectively); where the foundation model was supported by a cemented sabkha layer with a cement content of 5% and a thickness ratio of 0.2, the value and rate of pulse loading that subjected the foundation were 240 N and 50 blows/min, respectively. Figure 3 (a) indicates that the stress level at a depth of 2 cm is small. On the other hand, the stresses at a depth of 5 and 10 cm have a large value, reaching 11.7 and 20.5 kPa, respectively. The small value of stresses is due to the induced stresses decreasing with depth, and the stiffness of the sabkha underneath the cemented sabkha layer is low. Based on Figure 4(b), in the beginning, the maximum pore pressure at a depth of 2, 5, and 10 cm is 0.5, 0.61, and 0.80 kPa, respectively. With continuous repeated loading, the pore pressure was 0.30, 0.6, and 0.8 kPa at a depth of -2, 5, and 10 cm, respectively. The pore pressure variation at level -2 cm is due to the layer of cemented sabkha with a 1 cm thickness being partially impervious. Hence, the pore pressure is highest at the underneath layer and decreases with depth.

From stress and pore pressure time histories for each model, the maximum value of stress and pore pressure was measured and utilized to evaluate the liquefaction potential of sabkha soil. The stress ratio, r_u, is used to examine the liquefaction potential in the sabkha that underlies the cemented sabkha layer. The stress ratio r_u is defined as the ratio of pore pressure to stress. The liquefaction is triggered if the r_u is close to the unit (Kramer, 1996).

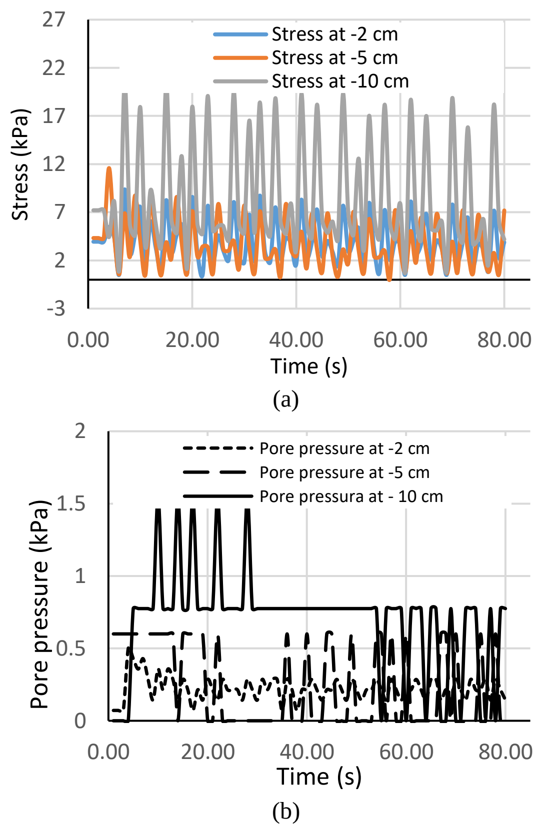
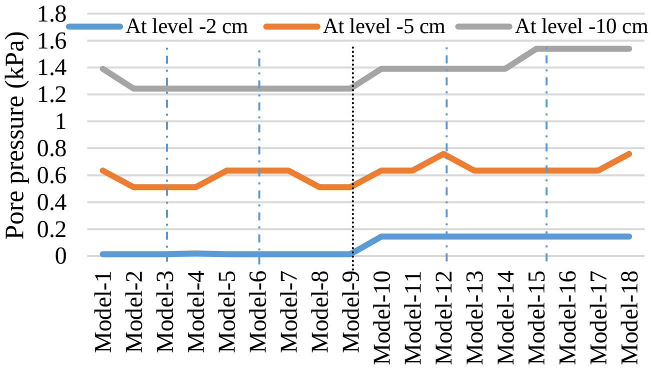
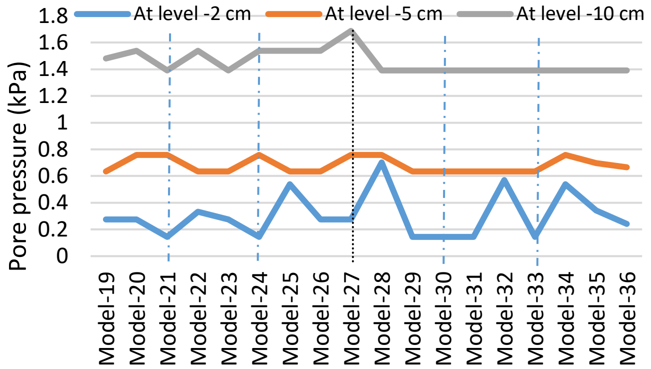


Figure 4 (a) stress time history and (b) pore pressure-time history, at several depths, at value, and rate of pulse loading of 160 N, 200 blows/min for cement content of 10% and thickness ratio of 0.2

Figures 4 and 5 present the maximum stress and pore pressure at three depths for 36 models, respectively. The pore pressure and stresses generally increase with the depth. This is due to the inertia force of the soil, which increases with depth. This force may be pronounced with a large value of repeated loading. In addition, the influence of cement content and thickness ratio of cemented sabkha layer leads to an increase in the pore pressure and the stresses in the sabkha layer that underlie the cemented sabkha layer. The inertia force depends on the mass of the foundation model, cemented sabkha layer, and the sabkha that is above the stress transducer and pore pressure gauge. They increase with increasing the cement content and thickness of the cemented sabkha layer. The rate of pulse loading has a significant impact on increasing the pore pressure. In addition, the stresses in the sabkha layer increase with increasing the magnitude of pulse loading and rate of pulse loading. The force of pulse loading and rate of pulse loading increase sabkha's stresses increases with increasing the thickness ratio due to the densification of the sabkha soil, which increases with increasing the thickness ratio. The densification of the sabkha leads to an increasing the inertia force. Based on these values shown in the Figures, the results reveal that the stress ratio increases with depth. The maximum value of r_u is ranged from 0.07 to 0.1. Therefore, no liquefaction potential is observed in the sabkha soil under the considered scenarios.



(a)

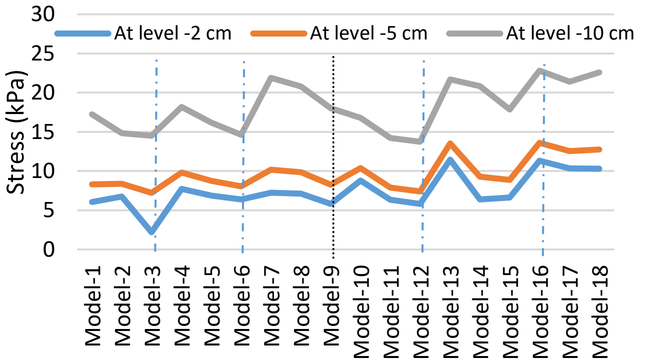


(b)

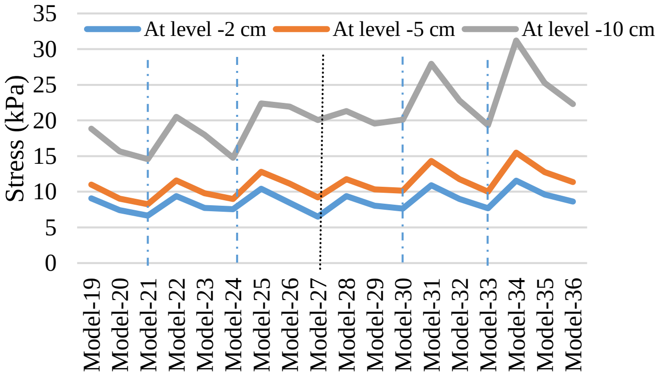
Figure 5 Pore pressure at the three depths of sabkha soil underneath cemented sabkha: (a) from Model 1 to Model 18 and (b) from Model 19 to Model 36

7. CONCLUSIONS

Several 1g small scale tests were carried out to investigate the deformation of block foundation model rested on several finite thicknesses cemented sabkha layer (thickness ratio of 0.2 and 0.4) with two cement content (5 and 10%). The foundation model was subjected to repeated loading; the pulse loadings of 80, 160, and 240 N were applied at several loading speeds as 200, 50, and 20 blows/min. The results reveal that the cement content significantly affects the sabkha soil's behavior compared to the thickness of cemented sabkha. The reduction in the maximum settlement value by increasing the cement content decreases with increasing of thickness ratio of cemented sabkha. In addition, the rate of pulse loading leads to an increase in the maximum settlement of at least 100 and 60% for thickness ratios of 0.2 and 0.4, respectively; these effects decrease with the increasing thickness of cemented sabkha. In terms of the liquefaction potential of sabkha soil that underlies the cemented sabkha layer, there is no liquefaction potential observed in sabkha soil when the value and rate of pulse loading subjected to the foundation are less than 240 N and 200 blows/min. The pulse loading force and rate of pulse loading have a significant effect on sabkha's stresses increase with increasing thickness ratio compared to the cement content added to the sabkha soil. The maximum value of r_u is ranged from 0.07 to 0.1. Therefore, there is no liquefaction potential observed in the sabkha.



(a)



(b)

Figure 6 Stresses at the three depths of sabkha soil underneath cemented sabkha: (a) from Model 1 to Model 18 and (b) from Model 19 to Model 36

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