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Experimental investigation on behavior of footings on contaminated deltaic soils

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ABSTRACT: Soil contamination can occur very frequently due to accidental leakage from industrial facilities. The aim of this paper is to investigate the behavior of surface footings resting on contaminated Delta soils. The experimental investigation comprised with laboratory model tests of surface strip footings resting on two sands. One of the tested soils was natural deltaic soil that was obtained from a site in the middle of the Nile Delta. The second sand was yellow sand that was obtained from a quarry that was located outside the boundaries of the delta valley. The contaminated soil depth is only about one width of the tested footings. The rest of the soil profile is uncontaminated soil. The tested soils were prepared at relative density of 50%. Two types of inorganic contaminants were used. One contaminant was acidic (pH <7) and another contaminant was alkaline (pH>7). Both contaminants were industrial wastes from two detergent factories. Each contaminant was mixed with 0, 2, 6 and 10% of each tested soil. The results were presented in the form of applied load or stress on strip footing versus settlement of the footings. The results provided a good ground to study the behavior of footings resting on soils contaminated with either acidic or alkaline substances.

1 INTRODUCTION

It is common practice, in Egypt, to dispose industrial waste of a factory in adjacent areas resulting in contamination of large areas of soil which, in turn, may influence foundations of existing structures or of those under construction. In general, contamination of soil results in changing its mechanical and compressibility properties and thus the behaviour of foundations on contaminated soils. The influence on behaviour depends on both type of soil and type of contaminant.

The early basic research of the engineering properties of clay minerals by Mesri in the late sixties is one of the important researches that contributed to uncovering the knowledge of influence of different contaminants on different clay minerals namely Kaolinite, Illite and montmorillonite and thus cohesive soils (Olson and Mesri 1970, Mesri and Olson 1970 and Mesri and Olson 1971). Such an influence depends on the physico-chemical properties of the contaminant on the pore fluid-clay mineral interaction. The influence of contaminant properties such as polarities, concentration of cations and number of cation charges; on the thickness of fluid double layer around the individual clay particle surface may cause possible aggregation or flocculation of individual particles to larger size flocs or aggregates. The increase in particle size from individual to group of particles may have significant influence on the mechanical properties of the cohesive soils. The influence of physico-chemical interaction on the pore fluid-soil particles system depends on the relative thickness of double layer around the soil or mineral particle as compared to the size of individual clay mineral or particle. As particle size increases or specific surface of the particle decreases (i.e. montmorillonite to illite to kaolinite), the influence of physico-chemical interaction decreases. The physico-chemical interaction on soil mineral particles becomes less significant as the shape of the soil mineral particles becomes less platy and be massive such as granular quartz and feldspar mineral (Mesri 1989).

As the physico-chemical interaction becomes less significant, other mechanical interaction may dominate the influence of contamination on behaviour of soils. One of the very important factors that influence the behaviour of soils is the viscosity of the fluid. The role of viscosity of the contaminant may signify due to lubrication at the soil particles or flocs surfaces. This paper focuses on the influence of contamination on the behaviour of sandy soils or silty sands..

Abouleid et al, (1986), studied the effect of oils having different viscosities on the behaviour of sandy soils with different coefficients of uniformity and revealed that for soil contaminated with small oil content (less than 5%), the thin layer of oil covering the surfaces of sand particles decreases the frictional resistance between sand surfaces and resist interlocking of particles during shear leading to a reduction in the angle of shearing resistance. Such conclusion was also confirmed by Evign and Das, (1992), .Al-Sanad et al. (1995), Shin et al.(1999), Shin and Das (2001), Ghaly (2001), Shin et al. (2002) Wegian, et al. (2004), Elkhouly et al. (2005), Ratnaweera and Meegoda (2006), Mashalah et al. (2007), and Nasr (2009). Al-Sanad et al. (1995) showed that the reduction in friction angles increased as viscosity of the oil increased.

Rabie (2009), and Rabei et al. (2009) investigated the change in shear strength of soil due to the exposure of sand and sand mixed with up to 40% plastic fines to inorganic contaminant of acidic nature. The results revealed a significant decrease of shear strength of pure sand for contaminant content less than 6 %. However, increasing contaminant content from 6 to 10% slightly increased the shear strength of soil. In general, the reduction was attributed to the lubrication influence of the contaminant on the sand particles. For the sand mixed with fines, there was no significant reduction in strength until the contaminant content of 6%. Further increase in contaminant content to 10%, measurable reduction in strength was observed. The observed behaviour was attributed to the fact that mixing fine with sandy soil prevents the contaminant to coat all the particles surfaces of sand matrix.

Studying the effect of oil contamination on the compressibility of sands, Al-sanad et al., (1995) concluded that the contamination of the sand with oil results in increase in compressibility of sands. Such conclusion was confirmed by Wegian, et al. (2004) and Elkhouly et al. (2005).

Rabie (2009) investigated the influence of contamination of sand and sand-fines mixtures on the compressibility of tested soils. The used contaminant was inorganic contaminant with acidic nature. The main conclusion of the investigation was that in general, the sand contamination increased the compressibility of the tested sands. The significance of the increase in compressibility decreases as percentage of added plastic fines increased in the sand.

With the exception of the work of Rabie et al. (2009), all the attention was given to clean sands. Even the work of Rabie et al. (2009) focused on the influence of contamination on the sand-plastic fines mixtures. It should be noted that the details of comprehensive study on both influence of inorganic contaminations of Delta silty sands on both the shear strength and compressibility will be the subject of future publication(s). This paper focuses on the strip footing behaviour of contaminated sands. However, the above listed literature is important to provide a solid ground for the explanation of the findings of this paper.

Shin et al.(1999) studied the influence of crude oil contamination sand on the bearing capacity of a model scale footing on contaminated sands. The oil content used varied from 0 to 4.2%. The conclusion was that the contamination caused reduction in the friction angle and thus reduction in the bearing capacity of a model scale footing with oil contamination. Such a conclusion was confirmed by Shin and Das (2001).

Nasr (2009) studied the influence of oil-contaminated sand on the bearing capacity characteristics and the settlement of strip footings at failure by conducting a series of model strip footing load tests carried out on both clean sand and oil-contaminated sand. It was concluded that oil contamination reduced the bearing capacity. It was also concluded that the increase of either the depth and/or the lateral extent of the contaminated sand layer decrease(s) the bearing capacity of the model footing while decrease in bearing capacity was associated with an increase in settlement. Any further increase in the depth of contaminated sand layer greater than 1.5 the footing width, did not result in further significant decrease in bearing capacity.

It should be noted that most of the model footings studies in the literature were carried out on clean sand. No attention was given to silty sands with significant non-plastic silt content. In addition, most of the focus was on the change in bearing capacity. No attention was given to the influence of contamination on the behavior of the load versus settlement curve.

2 MODEL STRIP FOOTING LOAD TESTS

Testing Equipment & Test Setup

The used equipment for model tests is a rigid steel box with inside dimensions of 1190 mm in length by 490 mm in width and 600 mm in depth with a steel base. Sides of the box were stiffened horizontally and vertically to avoid lateral movement at the time of loading the model strip footings. One side of the box has a detachable 20 mm thick rigid smoothed surfaces Plexiglas window to allow observing the movements of sand under the model footing during testing. The inside walls of the box are well polished and painted to minimize the frictional interaction between the tested materials and the walls. The box is attached to a steel loading frame. A schematic diagram of the loading frame and the box is illustrated in Figure (1).

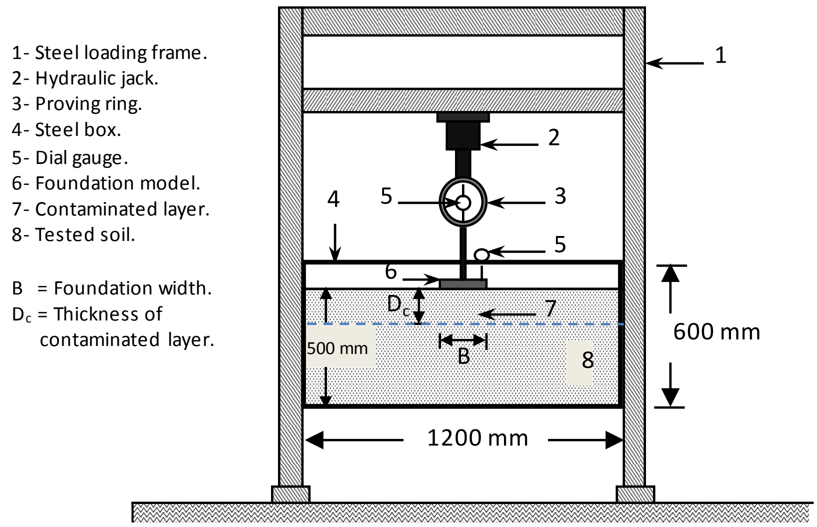


Figure 1. Schematic Diagram of Testing Equipment & Test Setup

Tested Soils

Two sands are used in the experimental program of this study. One of the sands is brought from a site at Al-Gharbeya governorate in the middle of Delta of the Nile River, herein referred to as "Talbant Qaisar Sand". The other sand used in the study, "Sadat Sand", is reference sand that is brought from a quarry near Sadat City outside of the river valley. Table (1) shows geological description of the sands and mineralogical composition based on X-Ray Diffraction Analysis of sand samples. The physical properties of the tested soils are determined based on physical and classification testing program that are conducted in accordance with the ASTM standards. The grain size distributions of the two sands are shown in Figure (2). Table (2) summarizes the physical and index properties of the tested soils as well as the unified classification of the tested soils.

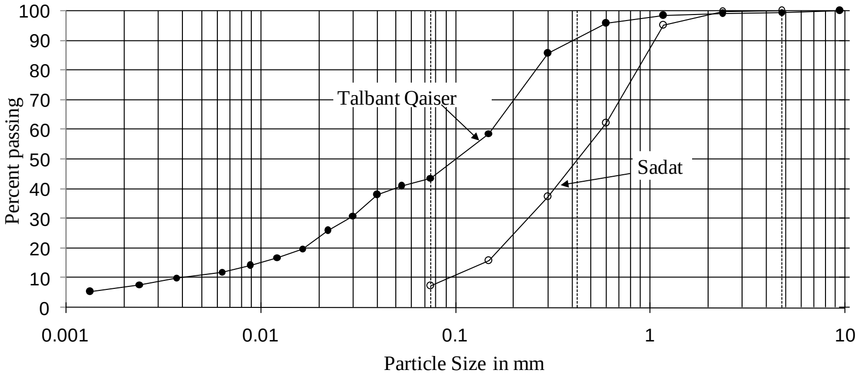


Figure 2. Particle-size distribution of the tested sands

Table 1. Geological Description & Mineralogical Composition of the tested Sands

SAND	SADAT	TALBANT QAISAR
Color	Yellow	Dark Grey
Geological Description	Medium-grained Moderately Sorted	Fine-grained Poorly Sorted & Argillaceous
Clay Minerals		
Montmorillonite, %	0	8.7
Illite, %	8.1	5.4
Non-Clay Minerals		
Quartz, %	76.9	45.5
Feldspar, %	9.3	24.5
Calcite, %	2.3	3.8
Dolomite, %	2.3	4.9
Muscovite, %	1.1	6.2

Table 2. Physical Properties & Classification of the tested Sands

SAND	SADAT	TALBANT QAISAR
Specific gravity	2.65	2.68
Effective size, D_{10}, mm	0.10	0.004
Median particle size, D_{50}, mm	0.43	0.10
Fines content, %	7.20	43.70
Clay fraction, %	-	11.0
Uniformity coefficient, C_U	5.90	-
Coefficient of curvature, C_C	0.98	-
Plasticity of fines	Non plastic	Non plastic
Classification (USCS)	SP-SM	SM
Maximum dry unit weight, $(\gamma_d)_{max}$, kN/m^3	18.49	16.91
Minimum dry unit weight, $(\gamma_d)_{min}$, kN/m^3	15.14	11.98
Dry unit weight, γ_d, kN/m^3	16.65	14.03
Relative density, D_r, %	50	50
Angle of internal friction, ϕ', ^{o} (secant at normal stress of 150 kPa)	49.7	36.0

Contaminants Properties

Two contaminants are used in this investigation. Both are waste products from detergent plants. One of the contaminants is acidic while the other is alkaline. The chemical composition and properties are shown in Table (4). The basic properties of the two contaminants are shown in Table (3).

Table 3. Contaminants Basic Properties

CONTAMINANT	ACIDIC	ALKALINE
Specific gravity	1.04	1.21
Unit weight, kN/m^3	9.74	11.34
Dynamic viscocity, μ, milliPa.s (23.5 ^{o} C)	1.30	13.82

Table 4. Chemical Composition and Properties of the Contaminants

CONTAMINANT	ACIDIC	ALKALINE	CONTAMINANT	ACIDIC	ALKALINE
T.D.S. (ppm)	995	61495	K+	36	5447
Al+++	-	115	Cl-	175	106
Ca++	122	580	SO_3	389	-
Mg++	50	91	HCO_3-	28	-
Fe++	-	38	SiO_2	18.1	31689
Na+	119	23416	PO_4---	4.2	-
			pH	5.69	12.89

Soil Deposit Preparation

A relative density of 50% was considered when constructing the ground of tested soils in the steel box. The corresponding dry unit weights of Sadat and Talbant Qaisar Sands are 16.65 kN/m^3 and 14.03 kN/m^3, respectively. The tested sand is placed inside the steel box in lifts; each lift is 50 mm in thickness. To achieve the desired dry unit weight, the weight of each lift was assessed depending on both the volume of the space to be filled and the targeted dry unit weight of the soil. Hence, after the surface of each lift is leveled, the sand (if needed) is compacted by tempering with a smooth wooden board. The lifts are continued till reaching the strip footing level that corresponds to sand thickness of 500 mm in case of testing non-contaminated soil. In case of considering a contaminated soil layer below the strip footing level, the non-contaminated soil targeted thickness is 400 mm.

Preparation of Contaminated Soil Layer

The tested sand is thoroughly mixed with each of the considered contaminant percentages (2%, 6% and 10%). The amount of the contaminant is calculated as a percentage by weight of the dry sand. The calculated weight of the contaminant is then mixed with the predetermined weight of the dry soil to fill in a 50 mm thick lift. The soil–contaminant mixture is then placed on top of non-contaminated soil in the steel box. The surface of the lift is then leveled and, if needed, is compacted by tempering with a smooth wooden board. Two lifts are placed with total thickness of contaminated soil layer under the strip footing is 100 mm.

Model Strip Footing & Loading Tests

The prepared soil mattress is overlaid by a rigid steel plate that is 20 mm in thickness, 100 mm in width and 480 mm in length. The loaded rigid plates are resting on the sand surface. The length of the footing is selected to be approximately equal to the width of the steel box to simulate a plain-strain strip footing loading condition. The width of the plate is adjusted and placed symmetrically at the centerline of the longitudinal direction of the steel box. In each test, loading the steel plate is gradually carried out using a hydraulic jack. A steel rod having a semi ball tip is attached to the jack in order to give a concentrated load on the steel plate. The steel plate has in the middle of its upper surface a bally shaped grove at which the tip of the steel rod shall be in contact with. This allows rotation of the plate in the longitudinal direction of the box during loading process. During the loading process, vertical movement is measured using a digital gage with an accuracy of 0.01 mm. In all tests, the loading is conducted until reaching a normalized vertical displacement to width of the footing ratio of nearly 25% or at which small increments in the applied load result in relatively large increase in the settlement.

3 TESTING PROGRAM

A total of 14 model strip footing load tests carried out on non-contaminated and contaminated sands. Table (5) shows summary of the testing program including all the constant and variable parameters considered in the study. In the described program, the relative density of the sand and thickness of contaminated sand, D_c, are kept constant. Other variables include type of sand, type of contaminant, and percentage of added contaminant.

Table 5. Summary of Model Testing Program

Series	Sand	Dr, %	D_c/B	Contaminant	Percentages, %	No. of Tests
1	Sadat Talbant Qaisar	50	0	-	0	2
2	Sadat		1	Acidic	2, 6 & 10	3
3	Sadat		1	Alkaline	2, 6 & 10	3
4	Talbant Qaisar		1	Acidic	2, 6 & 10	3
5	Talbant Qaisar		1	Alkaline	2, 6 & 10	3
Total						14

As mentioned earlier a comprehensive experimental study was carried out at University of Tanta on contaminated silty sands. Presenting and discussing the results of the study shall be the subject of another publication. The mentioned study includes sets of direct shear box tests on the tested sands presented in this paper. For sake of complementing the model tests results, direct shear tests results on specimens of Sadat and Talbant Qaiser sands mixed with percentages of acidic and alkaline contaminants are presented in this paper. In these tests, the sand is mixed with pre-determined percentage of a contaminant. The three percentages in Table (5) are used. Each of the prepared specimens is subjected to effective normal pressure of 150 kPa. The sample is then saturated and sheared.

4 RESULTS & DISCUSSION

Effect of Contamination on Shearing Resistance of Tested Sands

For sake of comparison among the results, the shearing resistance ratio (SRR) is introduced and defined in the following Equation:

$$SRR = \frac{\tan(\phi_{cont})}{\tan(\phi_{uncont})} \tag{1}$$

where ϕ_{cont} is the secant friction angle of contaminated sand and ϕ_{uncont} is the secant friction angle of uncontaminated sand. The SRR are plotted versus percent of contamination in Figure (3). Shown also on the same Figure, is a plot of same data showing secant friction angles versus percentage of contamination. The data in Figure (3) shows that for Sadat sand with fines content of 7% where the sand is still behaving as sand, the contamination of the sand is introducing a layer around the sand particles acting as lubricant that reduces the frictional resistance of the sand. The fact that alkaline contaminant has higher viscosity as compared to that of the acidic contaminant; explains the further reduction in the frictional resistance in case of alkaline contaminant as compared to acidic contaminant. This confirms the finding of Al-Sanad et al. (1995) considering the various viscosities of the oils tested.

Figure (3) shows also that considering 0% contamination, the increase in fines content from about 7% for Sadat sand to about 44% for Talbant Qaiser silty sand causes reduction in secant friction angle by about 62% dropping from 49^o to 36^o.

The silty sand Talbant Qaiser has fines content of 44%. Such high silt content makes the soil behave as silt with sand particles not really in contact with each other. However, the fact that the fines are nonplastic made the observed behaviour different from that observed by Rabie et al. (2009) in case of plastic clayey fines. According to Rabie et al. (2009), the plastic fines up to about 40% did not seem to significantly change the shearing resistance. In case of Talbant Qaiser sand with 44% nonplastic fines, the acidic contaminant caused reduction in the frictional resistance similar to that caused by contamination of Sadat sand with acidic contaminant. On the other hand, contamination of Talbant Qaiser with alkaline contaminant caused an increase in the shearing resistance followed by slight decrease in frictional resistance with further increase in percentage of contamination. The more viscous alkaline contaminant seems to aggregate the fine particles changing to a certain extent the size of fraction of the particles from silt size to sand size particles resulting in increase in shearing resistance. Further increase in the alkaline contaminant causes lubrication to sand size particles and thus the observed behaviour is explained.

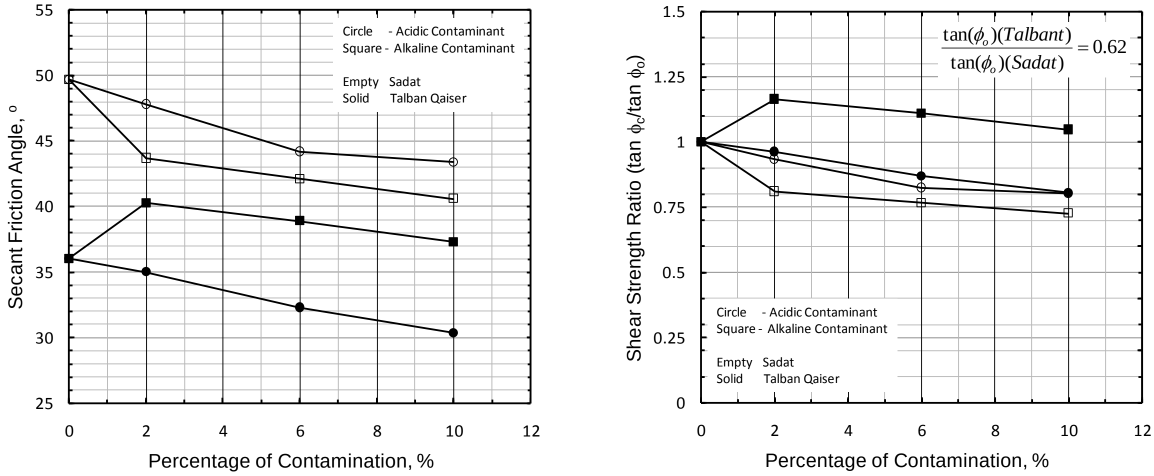


Figure 3. Summary of direct shear box tests results showing the influence of contamination on shearing resistance. (left) secant friction angles versus Percentage of contamination (right) Shear strength ratio versus Percentage of contamination.

Effect of Contamination on the behavior of strip footing load tests

The load per unit area versus settlement relationships for the strip footing load tests in this study are shown in Figure (4).

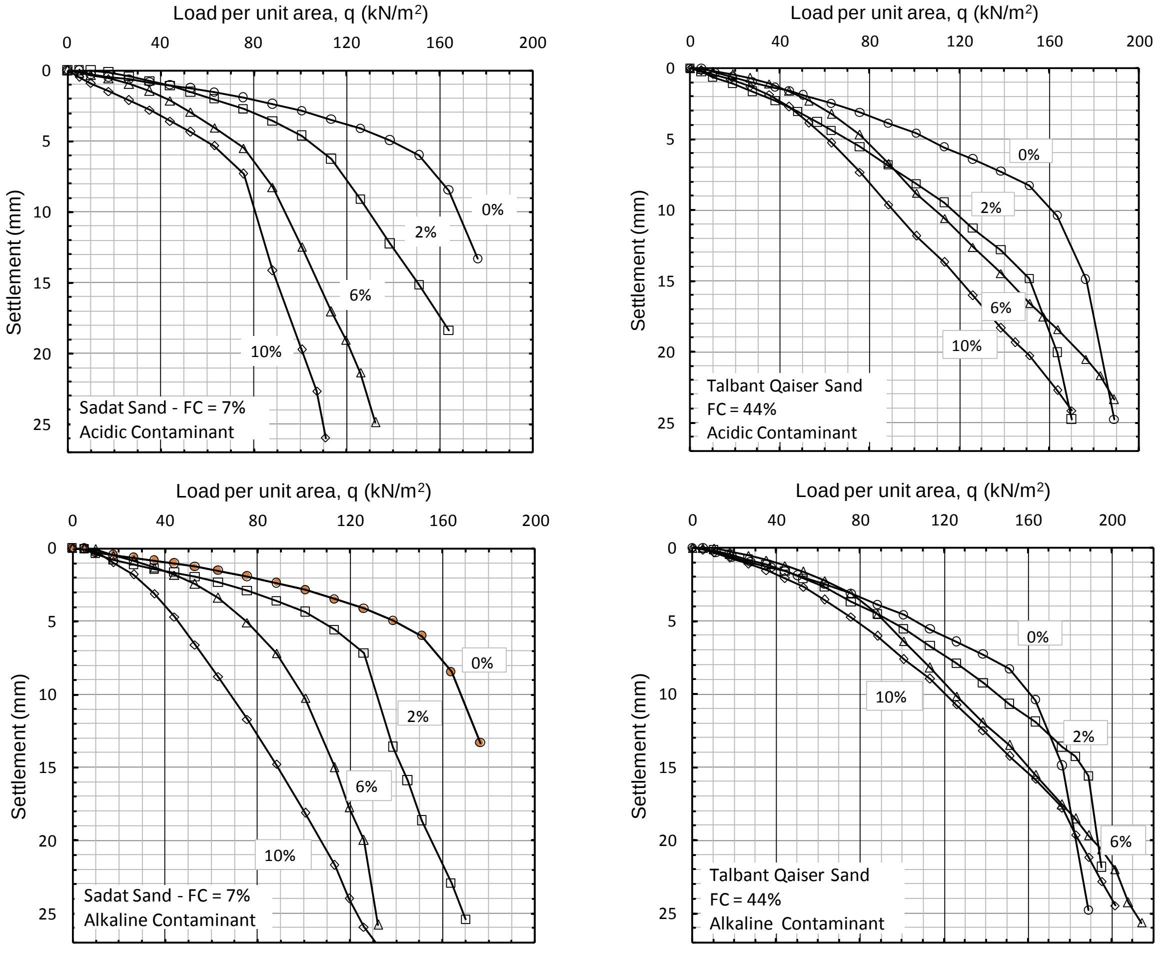


Figure (4) Results of strip footing load tests on contaminated and non-contaminated sands.

In general, the load per unit area versus settlement relationships observed can be divided to three categories as shown in Figure (5). The first category is the general failure type of behavior that is showing a sort of distinct yielding or failure pressure that is defined as the pressure above which there is large increase in settlement for relatively small increment of stress. The second type is the non-yielding or compressing, in which there is a continuous compression with no distinct yielding stress. The third type of relationship is kind of combination of the first two types. In the third type, the curve starts with continuous compression type of behavior with a sort of yielding stress observed at very large settlement or what is called delayed yielding. It is thought that the second and third types of stress versus settlement curves are local failure. In the cases where the local failure is observed, the compressibility of the top contaminated layer is larger than that of the bottom uncontaminated layer. Such difference in compressibility forced the failure to occur in the top layer by excessive compression or sort of squeezing out from underneath the footing. The described behavior made it very difficult to determine the bearing capacity from the observed relationship in some cases.

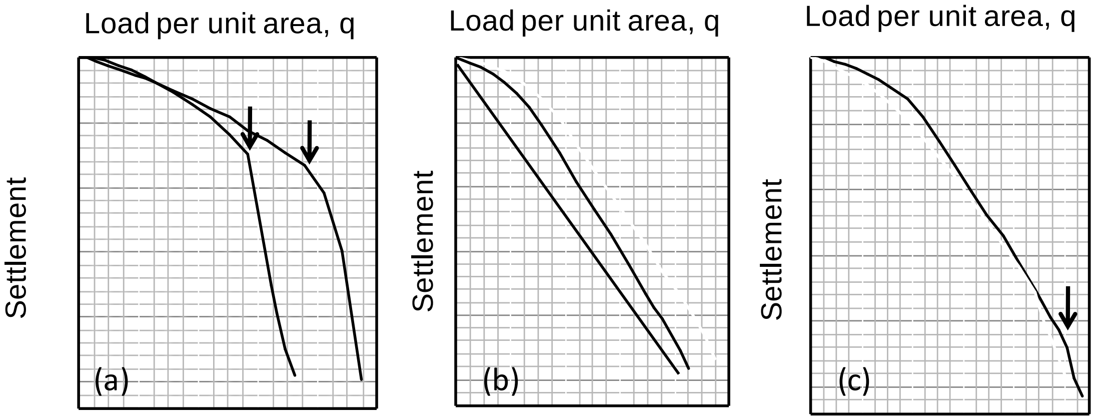


Figure (5) Types of load versus settlement relationships observed during this study – (a) General failure (i.e. yielding), (b) Non-yielding or compressing, (c) Yielding at large settlement – (b) & (c) Local failure

Effect of Contamination on the Ultimate Bearing Capacity

Depending on type of failure or the resulting stress versus settlement relationship, if it could be determined, the ultimate capacity of the footing is obtained from stress settlement curves at the point where the slope of the curve first reaches zero or a steady minimum value. For ease of comparison, the bearing capacity ratio BCR is used and described in the following expression:

$$BCR = \frac{(q_{ult})_{cont}}{(q_{ult})_{uncont}} \qquad (2)$$

where $(q_{ult})_{cont}$ and $(q_{ult})_{uncont}$ are ultimate bearing capacities for contaminated sand and uncontaminated sand, respectively. The bearing capacity factors versus percentage of contamination are shown in Figure (6.a). For ease of explanation, the shear strength ratios versus percentage of contamination presented earlier in Figure (3) are shown in Figure (6.b). If the ultimate bearing capacity in a test could not be determined due to type of failure, then a question mark is indicated on the plot. Comparing the two plots in Figures (6.a and 6.b), it can be easily shown the general similarity of trend between the shear strength ratio and bearing capacity ratio versus percentage of contamination.

Influence of Contamination on the Compressibility under the Strip Footings

The secant modulus of sub grade reaction, k_s, which is the stress q to settlement S ratio as a measure of compressibility is determined in the non yielding part of the stress versus settlement curve. For ease of comparison, the modulus of sub grade reaction ratio k_sR is used and described in the following expressions:

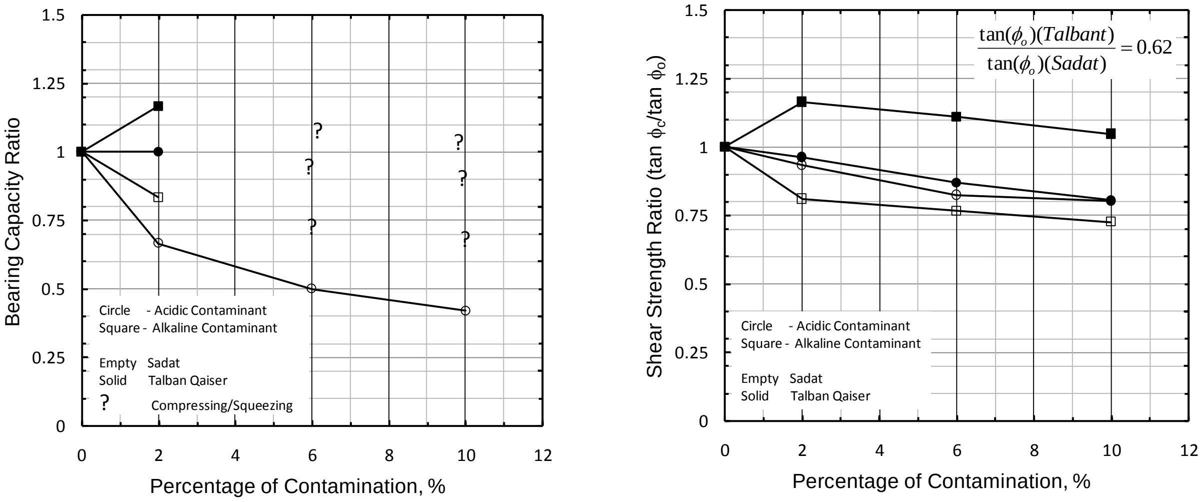
$$k_s R = \frac{k_{s-cont}}{k_{s-uncont}} \qquad (3)$$

where $k_{s\text{-}cont}$ and $k_{s\text{-}uncont}$ are modulus of sub grade reactions for contaminated sand and uncontaminated sand, respectively. Figure (7) shows the relationship between KR versus percentage f contamination. Shown also on the same Figure, is the ratio of modulus of sub grade reaction of Talbant Qaiser Sand to that of Sadat sand. The mentioned ratio shows that in case of zero contamination; the increase in fines content from 7% (Sadat) to 44% (Talbant Qaiser) decreases the modulus by about 33%.

Figure (7) shows that in general, contamination of the sand causes reduction in modulus of sub grade reaction ratio which means decrease in modulus or increase in compressibility of the sand. This is due to the introduction of lubrication agent to particle surface contacts facilitating the relative movement among particles in response to loading thus increase in compressibility.

It is also found that contamination with alkaline contaminant causes more reduction in k_s as compared to that caused by acidic contaminant. Such behaviour could be explained by the higher viscosity of the alkaline contaminant as compared to that of the acidic contaminant.

It is also found that contamination causes more reduction in modulus (k_s) in cases Sadat sand with fewer fines content as compared to the reduction in k_s in case of Talbant Qaiser with high fines content. This is similar to what was observed by Rabie (2009)



(a) Bearing capacity ratio from strip footing load tests (b) Shear strength ratio from direct shear box results

Figure 6. Comparison between shear strength ratio and bearing capacity ratio from the results of this study.

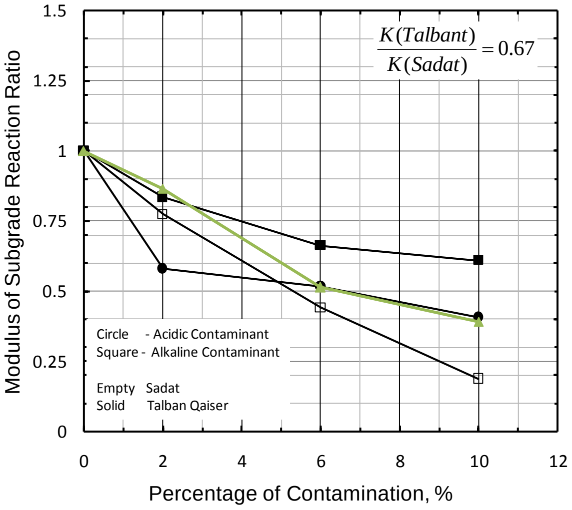


Figure 7 Modulus of subgrade reaction ratio versus percentage of contamination based on the experimental work in this study

6 CONCLUSIONS

From the results of direct shear tests, contamination of Sadat sand with fines content of 7% causes a reduction in shearing resistance due to lubrication effect at particle surfaces. Due to higher viscosity, alkaline contaminant causes more reduction in shearing resistance as compared to that caused by acidic contaminant In case of Talbant Qaiser sand with 44% nonplastic fines, acidic contaminant causes reduction in the shearing resistance due to lubrication effect, while higher viscosity alkaline contaminant causes silt size particle aggregation to larger sand size particles causing increase in shearing resistance.

The changes in ultimate bearing capacity due contamination of the soils are similar to the changes in shearing resistance due to contamination with differences in the amount of changes due to influence of compressibility of contaminated soil during footing load tests.

Three types of the stress versus settlement relationships could be recognized. The first type is yielding behavior that corresponds to general failure. The other two shapes are continuous compression non yielding or continuous compression with yielding at very large settlement. The last two are judged to correspond to local failure that takes place when the compressibility of the contaminated soil layer is relatively larger than that on non-contaminated underlain layer. Such a difference in compressibility forces the failure to take place in the surface contaminated layer.

Contamination of the sand causes reduction in modulus of sub grade reaction due to lubrication at the particle surface contacts facilitating the relative movement among particles in response to loading. Alkaline contaminant causes more reduction in modulus as compared to that caused by acidic contaminant due to the higher viscosity of the alkaline contaminant. Contamination causes more reduction in modulus in Sadat sand with fewer fines content as compared to the reduction in modulus recorded in Talbant Qaiser with high fines content.

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