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Experimental and numerical investigation on circular footing subjected to incremental cyclic loads

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Abstract

The results of laboratory model tests and numerical analysis on circular footings supported on sand bed under incremental cyclic loads are presented. The incremental values of intensity of cyclic loads (loading, unloading and reloading) were applied on the footing to evaluate the response of footing and also to obtain the value of elastic rebound of the footing corresponding to each cycle of load. The effect of sand relative density of 42%, 62%, and 72% and different circular footing area of 25, 50, and 100cm^2 were investigated on the value of coefficient of elastic uniform compression of sand (CEUC). The results show that the value of coefficient of elastic uniform compression of sand was increased by increasing the sand relative density while with increase the footing area the value of coefficient of elastic uniform compression of sand was decreases. The responses of footing and the quantitative variations of CEUC with footing area and soil relative density obtained from experimental results show a good consistency with the obtained numerical result using "FLAC-3D".

Keywords: Experimental model; Numerical model; Coefficient of elastic uniform compression; Circular footing; Footing area; Sand relative density

1. Introduction

Machine foundations require the special attention of a foundation engineer. In addition to static loads due to the weight of machine and the foundation, loads acting on such foundations are often dynamic in nature due to the action of the moving parts of the machine. While these dynamic loads are generally small, as compared to the static load, they are applied repetitively over a very large number of loading cycles. Therefore it is necessary that the soil behavior be elastic, or else deformation will increase with each cycle of loading until the unstable soil behavior develops.

Research into the behavior of soil and shallow foundations subjected to dynamic loads was initiated during the 1960s and 2000s. Both theoretical and experimental studies of the dynamic behavior of shallow foundations have been reported by several researchers out to understand the load-settlement relationship of footings and also the relationship between footing settlement and the number of load cycles [1-6]. Experimental observation of the load-settlement relationships of square surface foundations supported by sand and clay and subjected to transient loads were reported by [1, 7]. Raymond and Komos [2] conducted laboratory model tests on strip surface foundations supported by sand and subjected to cyclic loadings of low frequency to determine the relationship between foundation settlement and the number of load cycles. Das and Shin [5] reported the results of some laboratory model tests conducted to evaluate the permanent settlement of a surface strip foundation on a saturated clayey soil layer while being subjected to a combination of static and cyclic loading of low frequency. This investigation indicated that the initial rapid settlement due to cyclic load application takes place during the first ten cycles of loading, constituting about 60% to 80% of the total settlement and an equilibrium period is reached after about 15000 cycles.

Das [8] conducted a laboratory model tests for settlement of surface square foundation supported by a medium dense reinforced sand bed and subjected to cyclic loading of low frequency. His test results indicated that the geogrid reinforcement can act as a settlement retardant for dynamic loading conditions on the foundations. Raymond [9] investigated the performance of a thin layer of granular

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material, whether reinforced or not, when acting as a foundation material for a repeatedly loaded surface footing using a plane strain model test. He reported that the effect of aggregate reinforcement was observed to be even more beneficial when the foundation soil was in a loose condition and noted the beneficial effect of ballast reinforcement in reducing plastic settlements.

Khan et al. [10] studied the cyclic load deformation behavior of soil-fly ash layered system using different intensities of failure load with varying confining pressures and number of cycles. They evaluated the resilient modulus, permanent strain and cyclic strength factor from the test results and compared to show their variation with varying stress levels. Their test results revealed the dependency of consolidated undrained shear strength tests of soil-fly ash matrix. Nayeri and Fakharian [11] carried out a series of pullout tests on geogrid embedded in sand under cyclic forces. The effects of various parameters include normal pressure, geogrid stiffness, soil relative density, and type of loading path on the pullout resistance and accumulation of displacements of sand-geogrid under cyclic loading conditions was investigated.

Moghaddas Tafreshi and Khalaj [12] performed an experimental study on small-diameter pipes buried in reinforced sand subjected to repeated loads to simulate the vehicle loads. They reported that deformation of the pipe and also, settlement of the soil surface increased rapidly during the initial loading cycles; thereafter the rate of deformation reduced significantly as the number of cycles increased. Moghaddas Tafreshi et al. [13] used the artificial neural network for predicting the vertical deformation of high-density polyethylene (HDPE), small diameter flexible pipes buried in reinforced trenches subjected to repeated loadings. Their experimental data from tests and data predicted from neural network show that the vertical diametric strain (VDS) of pipe embedded in reinforced sand depends significantly on the relative density of sand, number of reinforced layers and height of embedment depth of pipe. Moghaddas Tafreshi and Dawson [14] carried out a series of laboratory model tests on strip footings supported on geotextile reinforced sand beds under a combination of static and repeated loads. They were found that the response of footing under the first few cycles is a significant behavioral characteristic of footings and also; with increasing the number of cycle loads, the rate of footing settlement reduced significantly until its value becomes stable or failure occurred due to excessive settlement. Khodaii and Fallah [15] simulated an experimental program of repeated loading on the asphalt mixture specimens. Their results indicated that geosynthetic reinforced specimens exhibited resistance to reflection cracking as a significant reduction in the rate of crack propagation and rutting in reinforced samples compared to unreinforced samples. Behbahani and Sahaf [16] presented a mathematical model for predicting the mechanical characteristics of asphalt pavements under dynamic loadings.

All the studies cited above indicate that there are no particular attentions on the responses of footing under incremental cyclic load and the value of Coefficient of Elastic Uniform Compression of soil; CEUC which is known as an most important parameter in designing a machine foundation [17]. In the research described here, and in order to develop a better understanding of the behavior of footings supported on sand bed under incremental cyclic loads (similar to cyclic-plate-load test) a series of laboratory, pilot scale tests were performed. The influences of three sand relative densities of 42%, 62% and 72% and three circular footing area of 25cm^2, 50cm^2 and 100 cm^2 on the variation of CEUC were investigated. Numerical simulation was also carried out on the model test, using FLAC-3D, to show compatibility of the numerical analysis with the test. It needs to be pointed out, however, that the results of this study may be somewhat different to full-scale foundation behavior in the field, although the general trend may be similar, so this paper attempts to study a point of this phenomenon.

2. Experimental Study

2.1. Test Equipment

The test equipment to prepare a test consists of four main parts which a brief description of each part is as follows:

The tests were performed in a tank with length and width of 650 mm, and height of 600 mm. The rigidity of the tank was guaranteed by using four rigid wooden plates of 40 mm thickness, in the three sides and bottom of the tank and its front face consisted of a plexi-glass sheet of 20 mm thickness supported by a strong solid brace of box section of 30x60 mm dimensions. According to the preliminary tests the measured deflection of the side faces of the tank proved to be negligible and in the ranges to satisfy the rigidity of the system.

The method used to deposit the soil in the testing tank at a known and uniform density was based on the raining technique [18]. A moveable steel tank of 300x300x450 mm (300 mm in length, 300 mm in width and 450 mm in height), ending into an inclined funnel system outlet was mounted above the testing tank and used as a hopper to pour the testing material from different heights. A simple sliding system of a perforated plate was provided in the outlet of the funnel to start or stop raining the soil. Different perforated plates and height of fall could be used to change the flow of raining. Before using the hopper for depositing the soil in the tank, the raining device was calibrated by different heights of pouring and various perforated plates. Consequently, the required height of pouring and perforated plate to get the desired density can be selected for a special test.

Loading system includes of the loading frame, the pneumatic cylinder, and the controlling unit. The loading frame consists of two stiff and heavy steel columns and a horizontal beam that support the pneumatic cylinder. The two pneumatic cylinders which have the internal diameters of 80 and 160 mm may produce monotonic or cyclic loads depending on the intensity of the input compressed air.

A data acquisition system was developed in such a way so that all loads and settlements could be read and recorded automatically. The system was able to read the data from sixteen channels simultaneously. A S-shaped load cell with an accuracy of ±0.01% full scale was also used and placed between the loading shaft and footing with a capacity of 15 kN to precisely measure the pattern of the applied load on the trench surface. Two linear variable differential transformers (LVDTs) with an accuracy of 0.01% of full range (100 mm) were placed on the two sides of the footing model to provide an average settlement of the footing during the repeated loads. To ensure an accurate reading, all of the devices were calibrated prior to each test. The general view of the test equipment is shown in Figure 1.

2.2. Soil

The soil used in this study is a relatively uniform silica sand of grain sizes between 0.07 and 1.24 mm and specific gravity of 2.67 (G_s=2.67). The grain size distribution of this sand is also shown in Figure 2. The properties of the sand, which is classified as SP in the unified soil classification system, are tabulated in Table 1. In order to study the effect of the soil density on the coefficient of elastic uniform compression of soil (CEUC) of footing on the soil, three different relative densities (D_r): 42% (relatively loose), 62% (medium dense), and 72% (relatively dense) were selected. These relative densities were achieved in the test tank using the sand raining technique by changing perforated plates and height of fall.

Fig. 1. The general view of the test equipment.

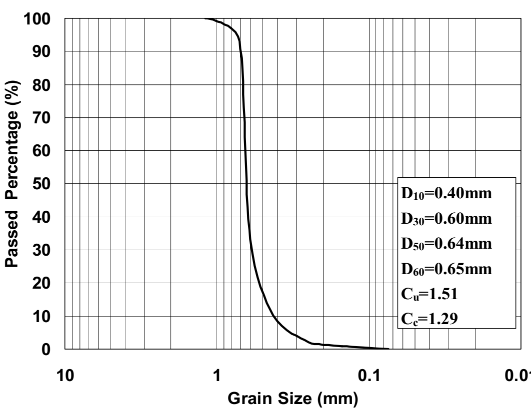


Fig. 2. Particle size distribution curve.

2.3. Preparation of Model Test

To prepare the uniform backfill in the test tank, the raining method was used. The required height of pouring and perforated plate to get the desired density can be selected for a special test and finally the soil was poured to the tank at desired relative densities. Circular rigid steel plates measuring 25, 50, and 100 cm^2 in area and 20 mm in thickness were selected as footings. The bottom of the footing was made rough by covering it with epoxy glue and rolling it in sand. A load cell was placed in the loading shaft to record the applied loads. Also two LVDTs were placed on the either sides of the footing model accurately to measure the settlement of footing during cyclic loadings. Also, in order to provide vertical loading alignment, a small semispherical indentation was made at the center of the footing model.

2.4. Testing Program

To study the effect of relative density of sand, Dr and footing area on the load-settlement behavior of the footing and Coefficient of Elastic Uniform Compression of soil (CEUC), 27 tests in different series were planned and carried out in this study. The static tests have been done to estimate the maximum value of load which applies in last step of incremental cyclic load tests (to avoid the failure of sand beneath the footing). The details of the testing scheme are given in Table 2. Some of the tests listed in Table 2 were carefully repeated to examine the performance of the apparatus, the accuracy of the measurements and the repeatability of the system. Some of the tests were repeated two or three times to verify the repeatability and consistency of the test data. The same pattern of load-settlement relationship with difference of up to 10% were obtained which shows that the developed procedure and technique produce repeatable tests within the bounds that may be expected from testing geotechnical apparatuses.

Table 1. Physical properties of soil

Description	Value
Coefficient of uniformity, C_u	1.62
Coefficient of curvature, C_c	1.38
Effective grain size, D_{10} (mm)	0.40
D_{30} (mm)	0.60
Medium grain size, D_{50} (mm)	0.64
D_{60} (mm)	0.65
Maximum void ratio, e_{max}	1.12
Minimum void ratio, e_{min}	0.55
Moisture content (%)	0
Specific gravity, G_s	2.67
Friction angle, φ (degree)	
D_r=42%	30.5
D_r=62%	35.7
D_r=72%	38.6

Table 2. Scheme of the static and cyclic tests for circular footing on sand bed.

Test Series	Type of tests	No. of Tests	Sand relative density, D_r (%)	Footing area (cm^2)
1	Static	3+1*	42, 62 and 72	25
		3+1*	42, 62 and 72	50
		3+1*	42, 62 and 72	100
2	Incremental cyclic load	3+2*	42, 62 and 72	25
		3+2*	42, 62 and 72	50
		3+2*	42, 62 and 72	100

*Indicates duplicate tests performed to verify the repeatability of the test data

2.5. Pattern of incremental cyclic loadings

The history of cyclic loading on the footing was selected based on the cyclic plate loading test. Figure 3 shows the typical time history of incremental cyclic loading and unloading on the footing at the rate of 1 kg/sec. As it can be seen, the first increment cyclic is kept constant for rather long times until no further settlement occurs or until the rate of settlement becomes negligible. Then the entire load is removed and the footing is allowed to rebound. The cycles of incremental loading, unloading and reloading are continued until the estimated load value has been reached. The numbers of the load increments are such that the estimated load is reached in five increments. The values of the ultimate load and the maximum applied load in cyclic tests have been obtained from the static tests which are shown typically in Figure 4.

3. Results

In this section, the test results of the laboratory model and numerical analysis are presented. A discussion focused on the response and elastic rebound of the footing. Furthermore, the effects of different parameters including sand relative density and footing area on the value of Coefficient of Elastic Uniform Compression of sand, CEUC are presented.

3.1. Experimental results

3.1.1. Static tests

The solid lines in Figure 4 present the experimental results of the applied stress on footing with the settlement of the footing with area of 100 cm^2 for different relative density of 42%, 62% and 72%. From this figure, the key role of the soil density on the bearing pressure and settlement of the footing is quite evident. The increased stiffness of pressure-settlement responses indicates the enhancement in bearing pressure and the reduction in the footing settlement due to increase in the relative density of sand. Also, it depicts that the maximum bearing pressure occurs at a smaller settlement when the relative density of sand increases. For example, the values of ultimate bearing capacity for relative densities of 42%, 62% and 72% are 122, 178 and 238kPa at settlement level (s/D: ratio of settlement; s to footing diameter; D) of 19.5%, 14.1% and 12.5%, respectively. It can be attributed to the increase in the soil stiffness due to the increase in the density of sand which accommodates a large shear strain in soil beneath the footing. It results the enhancement in the bearing capacity and the reduction in the settlement of the footing. Also, the settlement of footing at a given bearing pressure decreases due to enhancement the soil relative density. The presentation of whole of the static results would have made the paper lengthy.

3.1.2 The general behavior under incremental cyclic loads

The experimental results of the applied cyclic loads, incrementally (loading, unloading and reloading) with footing settlement, for footing area of 100cm^2 , rested on sand with relative density of 62% and 72% is shown in Figure 5 (solid lines). It indicates that in each stage due to unloading, a small amount of settlement rebounds which named elastic or recoverable settlement (the amount of elastic rebound of the soil increases with increase in the stress level) while a major part of the settlement is plastic settlement and remains in the system. With an increase in the number of cycles of loading, unloading and reloading the permanent plastic settlement are accumulated gradually.

The elastic rebound of the footing/foundation bed corresponding to any stress level of loading can be evaluated from the data obtained during the loading, unloading and reloading (Figure 5). The load intensity versus the elastic

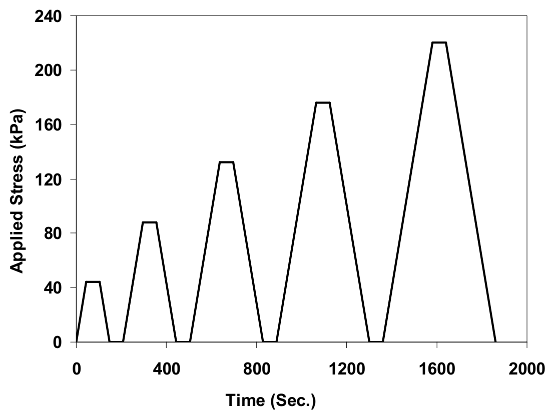


Fig. 3. Typical time history of incremental cyclic loads on footing**.**

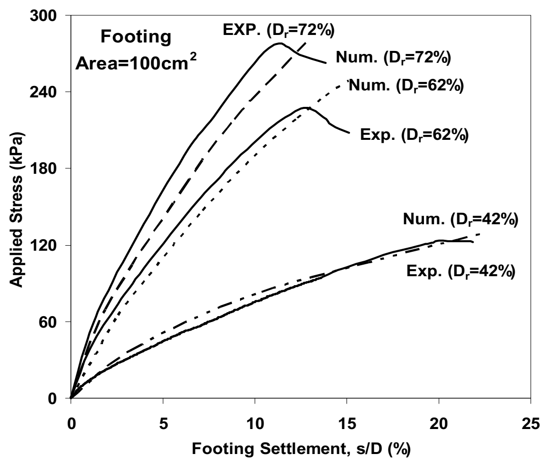


Fig. 4. Comparison between experimental results and finite element analysis for footing area of 100 cm^2 and three relative densities of 42%, 62% and 72% under static load (Exp: Solid line and Num: Dashed line).

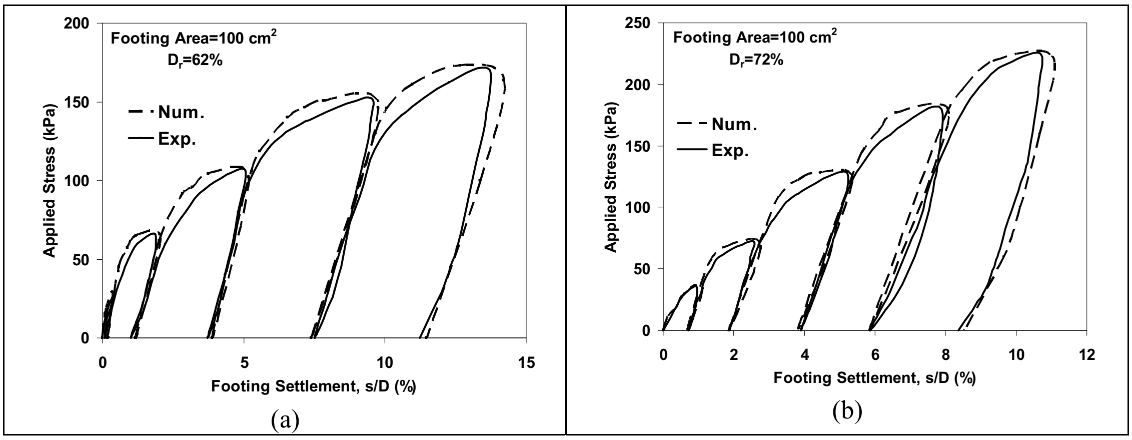


Fig. 5. Comparison between experimental and numerical results for footing with area of 100 cm^2 under incremental cyclic loading (a) D_r= 62% and (b) D_r=72% (Exp: Solid line and Num: Dashed line).

rebound can be plotted as shown in Figure 6 and Figure 7 for a given soil relative density and for a given footing area. The trend lines in Figure 6 and 7 are plotted from five data points corresponding to the five loading, unloading and reloading stages. The value of CEUC (in kPa/m) is the slope of trend line which can be calculated from the equation (1).

$$CEUC= P/S_e \quad (1)$$

In which P=corresponding load intensity in square centimeter (kPa) and S_e=elastic rebound displacement corresponding to removal of load P in meter.

3.1.3. The role of soil relative density

The elastic rebound of the circular footings on sand with three relative densities of 42%, 62% and 72% corresponding to each intensity of load are respectively shown in Figure 6a-c for footing area of 25, 50, and 100cm^2. These state that the slope of elastic lines which is representative of the coefficient of elastic uniform, CEUC, increases with an increase in the relative density of the sand, irrespective of footing area. For example, the value of CEUC for footing area of 100 cm^2 obtained 6.1E+4 kPa/m, 7.15E+4 kPa/m and 8.66E+4 kPa/m at relative density of 42%, 62% and 72%, respectively.

3.1.4. The role of circular footing area

Figure 7a-c shows the elastic rebound of the circular footing with three different areas of 25, 50, and 100cm^2, corresponding to each intensity of load and for sand relative densities of 42%, 62% and 72%, respectively. These state that the slope of elastic lines increase with decrease in the footing area, irrespective of sand relative density. In order to clarify the effect of footing area on coefficient of elastic uniform compression, the variation of CEUC (extracted of experiments) with area of circular footing for sand relative densities of 42%, 62%, and 72% is shown in Figure 8 (solid lines). This figure implies that the value of coefficient of elastic uniform compression, CEUC increases with decrease the footing area, irrespective of sand relative density. It is also clear that the percentage decrease in CEUC for variation of footing area between 25cm^2 and 50cm^2 is greater than those

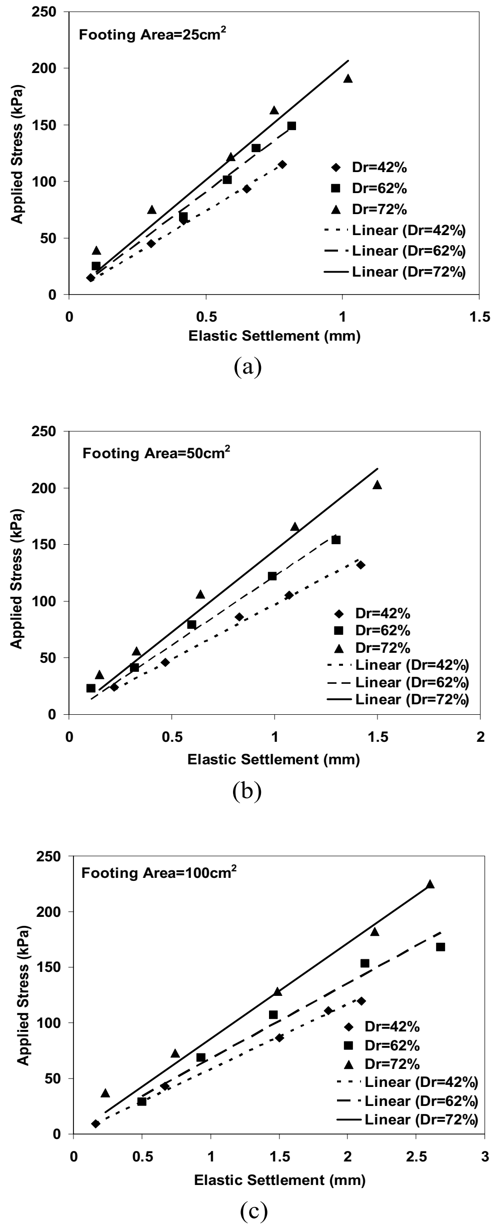


Fig. 6. Variation of applied stress versus elastic settlement for three sand relative densities (a) footing area of 25cm^2, (b) footing area of 50cm^2, and (c) footing area of 100cm^2.

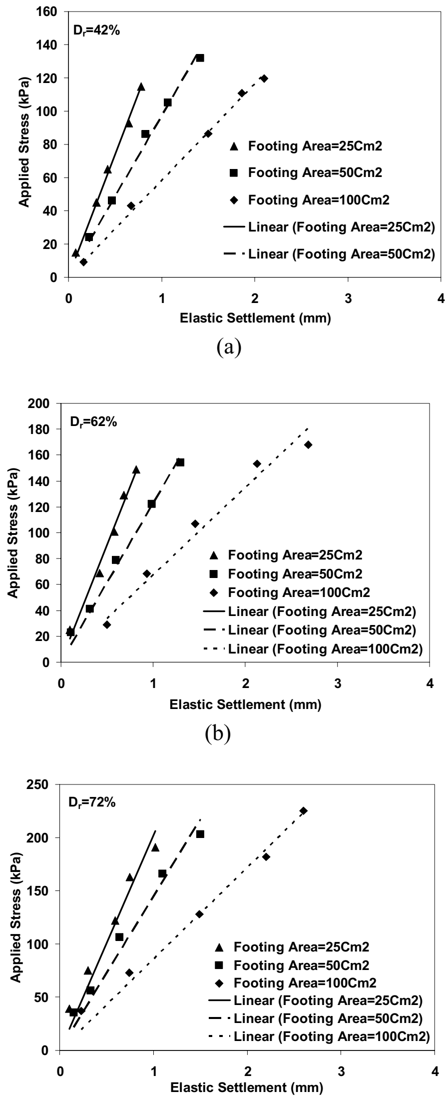


Fig. 7. Variation of applied stress versus elastic settlement for three circular footings, (a) D_r=42%, (b) D_r=62% and (c) D_r=72%.

for footing area between 50cm² and 100cm². Consider, for example, at relative density of 72%, the value CEUC is about 15.20E+4 kPa/m for footing area of 25 cm², whereas it is about 9.45E+4 kPa/m and 6.1E+4 kPa/m for footing area of 50cm² and 100cm², respectively. On the whole, Figure 8 confirms the effect of footing area on the value of coefficient of elastic uniform compression, CEUC suggested by Prakash [17]. He explained that from the reference value of $CEUC_0$ for the test block of contact area A_0, the value of CEUC for another area A (for A> A_0) may be obtained from the equation (2) as below:

$$CUEC = CUEC_0 \sqrt{\frac{A_0}{A}} \qquad (2)$$

This equation clarifies that with increase the footing area the value of coefficient of elastic uniform compression, CEUC decreases. It shows that the general trend and the qualitative variations of CEUC with footing area obtained

from experimental results agree favorably with the findings from equation (2).

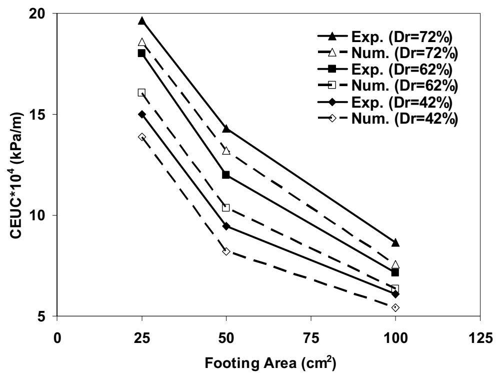


Fig. 8. Comparison of coefficient of elastic uniform compression, CEUC obtained from experimental and numerical model.

In order to compare the experimental values of CEUC with those obtained from the equation (2), the value of CEUC for footing area of 25cm² is considered as a reference value ($CEUC_0$) and then the predicted values of CEUC for footing area of 50cm² and 100cm² is calculated by equation (2). Figure 9a-b shows a comparison of experimental data and those obtained from the equation (2) for footing area of 50cm² and 100cm². It is shown that, the experimental values of CEUC are less than those predicted values for both footing area of 50cm² and 100cm². Also it can be seen that, the difference between predicted and experimental values of CEUC for footing area of 100cm² is greater than for footing area of 50cm².

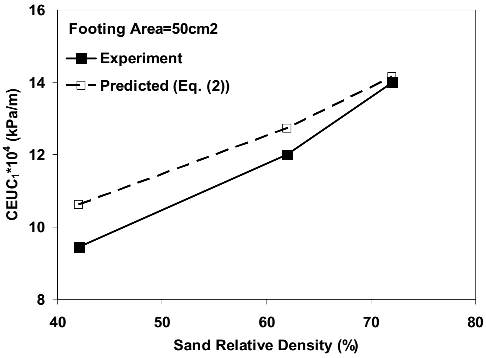
3.2. Numerical analysis

Finite difference analyses were performed to investigate the behavior of footing on sand under incremental cyclic loads and to evaluate the coefficient of elastic uniform, CEUC. The sand was modeled using the Mohr-Coulomb model. The finite difference model was first calibrated by laboratory model footing under static tests and then used to verify and to analyze the footing supported on sand in order to seek coefficient of elastic uniform, CEUC. To this end, several parameters were investigated, including sand relative density and area of circular footing.

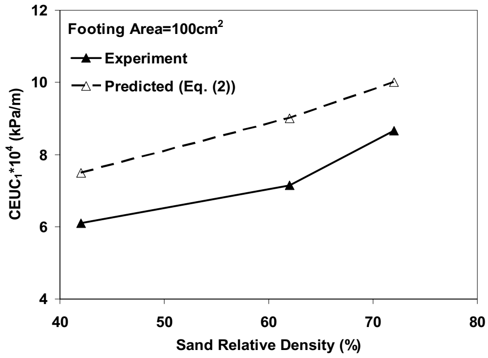
3.2.1. Finite difference model

The commercial finite difference program FLAC-3D [19] was used to study the behavior of circular footings with different diameters. A three-dimensional model was adopted to simulate the circular footing over sand (Figure 10). Because of symmetry toward the X-Z plane, only half of the footing and foundation bed was simulated. The geo-material was discretized using eight-node iso-parametric elements. Sensitivity analysis was also conducted to find the degree of mesh refinement to minimize mesh-dependent effects and converge upon a unique solution.

The finally adopted finite difference model, which has the dimensions of 650mm × 650 mm in plan and 600 mm in height exactly as same as the experimental model. The soil region is divided into a finite difference grid of 8112 brick elements as



(a)



(b)

Fig. 9. Comparison of predicted values (Eq. (2)) of CEUC with experimental results for (a) footing area of 50cm², and (b) footing area of 100cm².

shown in Figure 10. The model is symmetrically toward the X-Z plane. All vertical sides of the model in both X and Y directions and the bottom horizontal boundary in both the horizontal and vertical directions are constrained. Horizontal displacements at the interface between the footing and soil were restrained to zero, assuming perfect roughness of the interface and symmetry of the footing.

The footing is regarded as rigid, so applying load on the footing is equal to applying uniform vertical downward pressure at the nodes immediately underneath the footing. In the cyclic load analysis, the vertical load was applied in increments of 10000 to achieve a smooth response curve. In the incremental cyclic loads analysis, the running of the model carries on till the model is stabilized and no more deformation reach or the failure happen. Before applying the external load on the footing, the initial gravitational stress condition was established by attributing an initial stress state to the soil at grid points. Stress in the vertical direction is equal to the product of unit self-weight of soil and the distance of the grid points from the surface. Horizontal stresses are obtained using the coefficient of earth pressure at rest, K_0.

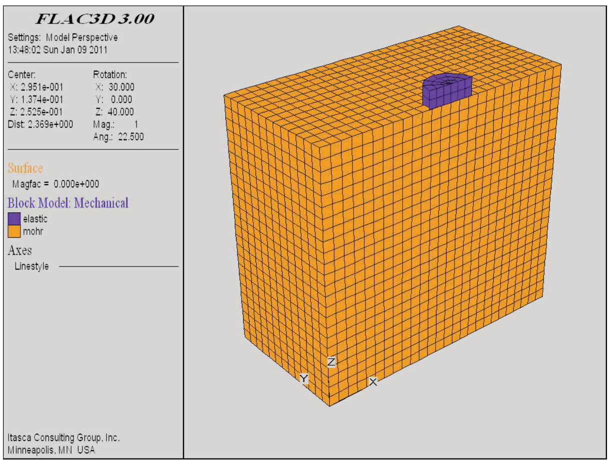


Fig. 10. 3D modeling of foundation bed and circular footing created with FLAC-3D.

3.2.2. Calibration and verification of numerical model

The finite difference model was first calibrated by comparing the results of model analyses with the static results of laboratory model tests on footing with area of 100 cm² for different relative density of 42%, 62% and 72%. Figure 4 presents the comparison between experimental results and finite difference numerical results, which shows that the numerical model can simulate the pressure-settlement behavior of footing under static load with good accuracy with the maximum difference of 10%. The properties of studied sand used to calibrate the numerical model at three relative densities of 42%, 62% and 72% are summarized in Table 3.

In order to verify the accuracy of the numerical model to predict the behavior of footing under incremental cyclic loads, Figure 5 compares the results of experimental and numerical model for footing with area of 100 cm² supported on soil with relative density of 42%, 62% and 72%. The numerical results agree reasonably well with the experimental data, indicating that the numerical simulation is promising for estimating the behavior of footing under incremental cyclic load (loading, unloading and reloading) and may conveniently be used as a tool to evaluate the coefficient of elastic uniform of sand foundation bed and distribution of stress and strain in the bed.

Table 3. Sand properties used in calibration of model.

Soil relative density (%)	Density (kg/m^3)	Friction Angle (Degree)	Poisson's Ratio	Shear Modulus (kPa)	Bulk Modulus (kPa)
72	1560	37.5	0.3	1700	4500
62	1510	35.5	0.3	1250	3000
42	1420	30.5	0.3	700	1700

Figure 8 compares the experimental data and numerical results for coefficient of elastic uniform compression, CEUC for sand relative densities of 42%, 62%, and 72% and footing area of circular footing of 25, 50 and 100 cm². Detailed comparisons show that the agreement between experiment and simulated numerical model is rather good. Also, the values of CEUC obtained from numerical model are conservative compared with experimental values. Consider, for example, at relative density of 72% the values of CEUC are 19.65E+4, 14.28E+4 and 8.66E+4 kPa/m for footing area of 25, 50 and 100 cm², respectively from the experimental model, whereas from numerical model these values are about 18.60E+4, 13.21E+4 and 8.14E+4 kPa/m for footing area of 25, 50 and 100 cm², respectively. Overall the maximum difference between experimental and numerical values of CEUC computed less than 20% which shows a good compatibility of the numerical analysis with the test. These agreements represent that, the simulated model introduced; here is a reliable model to predict the value of CEUC and the behavior of circular footing under incremental cyclic loading.

3.2.3. Stress and strain distributions

The vertical stress distributions within the foundation soil below the footing derived from the numerical analysis corresponding to the maximum load in the last loading cycle and were normalized against the applied footing stress. Figure 11 depicts the variation of normalized vertical stresses with normalized depth corresponding to the footing diameter below the footing with area of 100 cm² at three relative densities of 42%, 62% and 72%. The figure clearly indicates that the magnitude of vertical stress through the depth went down and decreased dramatically and then leveled out at a small ratio (less than 0.2) of applied stress near the depth of 2D (D is the footing diameter). As an example, the magnitude of vertical stress at a depth of half, one and two times of footing diameter are about 0.88, 0.65 and 0.2 of applied footing stress.

The figure clearly indicates that the magnitude of vertical stress through distributing the load applied on the footing onto a wider range in depth of foundation bed significantly reduces as the rate of reduction in vertical stress decreases with increase the depth of foundation bed. For example the magnitude of vertical stress at a depth of half, one and two times of footing diameter are about 0.88, 0.65 and 0.19 of applied footing stress.

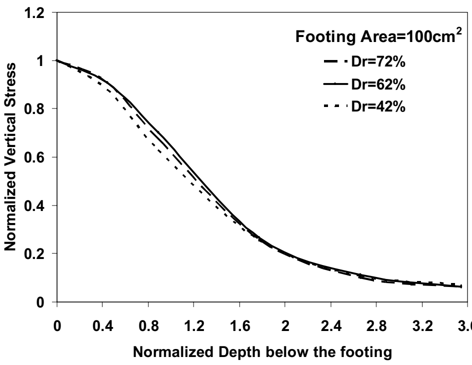


Fig. 11. Normalized vertical stress distribution for footing area of 100 cm² at three relative densities of 42%, 62% and 72%.

To show more evidences on the numerical analysis, Figure 12 which contains counters at the last loading cycle for relative dense soil (D_r=72%) and footing area 100 cm², is illustrated. Figure 12a shows the vertical stress bulb formed beneath the footing. This Figure states that far from the depth of 2D~3D (D is the footing diameter) beneath the footing, the vertical stress does not longer exist. Also this formed stress domain confirmed the accuracy of the boundary location in test setup; on the other hand, the footing's bearing capacity and footing settlement under cyclic loads are not affected by the boundary conditions. Furthermore, in Figure 12b shows the

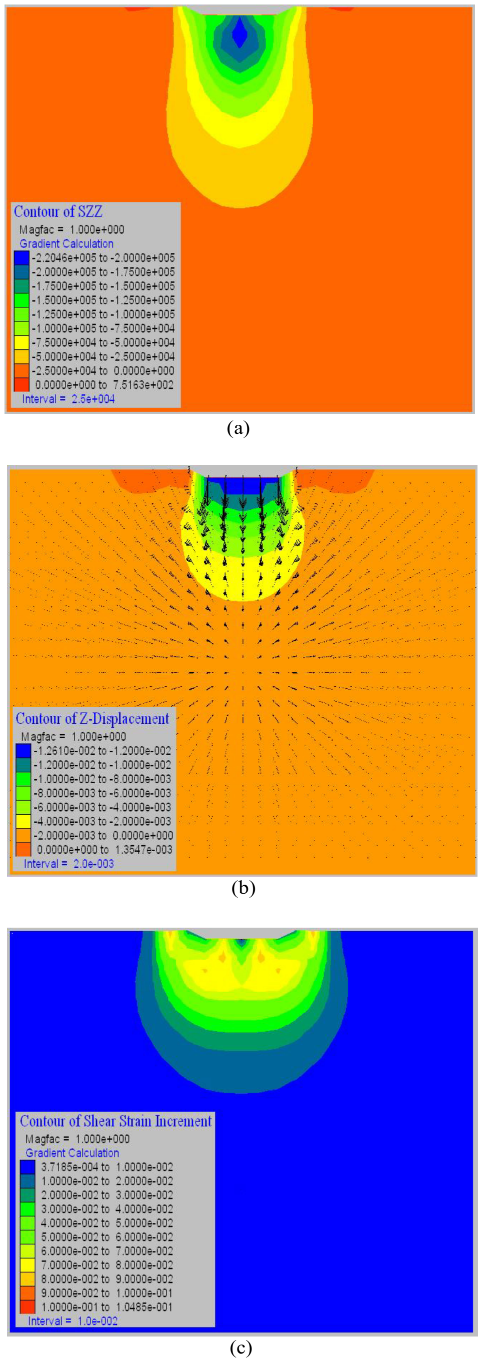


Fig. 12. Counters at the last loading cycle for relative dense soil (Dr=72%) and footing area 100 cm², (a) Vertical stress, (b) Displacement, and (c) Shear strain

displacement counters and the movement arrays formed at the end of the aforementioned test. It is found that the soil mass along the axis of the circular footing pushed down and the soil besides the footing is humped. Therefore, with regards to the Figure 12c which depicts the shear strain counters, it is obvious that dense soil provide a large global shear zone beneath the footing.

4. Conclusion

An experimental test program accompanied by numerical modeling with the aid of the FLAC 3D was employed to study the behavior of model circular footing under incremental cyclic loads. The investigations have been carried out on circular footing with three different diameters supported on sand beds at three relative densities. The test results have been used to assess and understand the properties of elastic rebound of soil and also to evaluate the effect of soil relative density and area of circular footing on coefficient of elastic uniform compression of sand, CEUC. On the basis of the experimental and numerical results obtained from the present investigations, the following conclusions can be drawn:

1. The amount of elastic rebound settlement of the soil corresponding to reloading of footing is small compared with plastic settlement. However the value of elastic rebound increases with increase in the stress level.
2. With increase in the number of cycles of loading, unloading and reloading the permanent plastic settlement of footing accumulates.
3. The value of CUEC of soil is significantly affected by the footing area as its value decreases with increase in the diameter of footing (footing area), irrespective of the soil relative density.
4. With increase in the soil relative density, the value of CEUC increases in a rather linear manner, irrespective of footing area.
5. The general trend and the qualitative variations of CEUC with footing area obtained from experimental results may be similar to the findings from equation (2) which confirms with increase the footing area the value of CEUC decreases.
6. The comparisons between experimental and numerical approaches show a good compatibility as the maximum difference between two approaches was obtained about 15%. These good consistencies represent that, the presented numerical model is a reliable model to simulate the behavior of footings under incremental cyclic loads and to evaluate the value of coefficient of elastic uniform of soil, CEUC.

Overall, qualitatively, the results presented herein provide an insight into the basic mechanism that establishes the incremental cyclic pressure versus settlement response of the sand bed and the value of coefficient of elastic uniform of soil, CEUC. However, there are some limitation points for the experimental results such as using only one type of sand and small size of circular footing width. Hence, although Milligan et al. [20] and Adams and Collin [21] in their studies on large- and small-scale tests on the behavior of granular soil showed that the general mechanisms and behavior observed in the small model tests could be reproduced at large-scale. Thus expansion of experiments on larger scale tests (with larger scale footings) together with field tests needs to be conducted at various conditions. For example, different footings (in size, shape and depth), different characteristics of soil and different particle size distribution of soil would be very useful to validate the present findings. This could be investigated in future research. On the whole, although, the experimental and numerical results of this study may be somewhat different, quantitatively, to full-scale foundation behavior in the field, the results could be helpful in designing large-scale model tests and especially, their simulating through numerical models.

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