CYCLIC LOADING ON FOUNDATION TO EVALUATE THE COEFFICIENT OF ELASTIC UNIFORM COMPRESSION OF SAND

S.N. Moghaddas Tafreshi [1], S.E. Zarei[2] and Y. Soltanpour[3]

[1] *Associate Professor, Dept. of Civil Engineering, K.N. Toosi University of Technology, Tehran. Iran*
[2, 3] *Ms, Dept. of Civil Engineering, K.N. Toosi University of Technology, Tehran. Iran*
Email: nas_moghaddas@kntu.ac.ir,

ABSTRACT:
The coefficient of elastic uniform compression of soil (C_u) is the most important parameter to be determined in designing a machine foundation. This paper presents the results of cyclic-footing-load tests from the laboratory-model tests on square footings supported by a sand bed. The various intensity of cyclic load (loading, unloading and reloading) apply on the footing and then the elastic rebound of the footing corresponding to each intensity of loading obtains during the tests to determine the coefficient of elastic uniform compression of sand. The influence of sand relative densities of 45%, 63%, and 78% on behavior of footing under both static and cyclic loads case investigated. The results indicate that with increasing the relative density of soil the value of C_u increases. Finally the numerical analysis of footing under static and incremental cyclic loading is carried out by the FLAC^{3D} program. The results show that the numerical results are in good agreement with experimental results.

KEYWORDS:
Laboratory test; Cyclic loads; Coefficient of elastic uniform compression; Machine foundation

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 dynamic in nature. In general, a foundation weighs several times as much as a machine. Also, a dynamic load associated with the moving parts of a machine is generally small as compared to its static load. In this type of foundation a dynamic load applies repetitively over a very large period of time but its magnitude is small, and it is therefore necessary that the soil behavior be elastic, or else deformation will increase with each cycle of loading until the soil becomes practically unacceptable. Shvets and Nazha (2000) investigated the influence exerted by anisotropy of the deformation properties of soil foundation beds on the elastic characteristics used in dynamic analyses of machine-bearing foundations. They suggested that correction factors dependent on the degree of anisotropy of the soil should be used in the analyses. DeMerchant et al. (2002) performed an experimental study to investigate the beneficial effect of geogrid on subgrade modulus of lightweight aggregate beds. Moghaddas Tafreshi & Khalaj (2008) performed an experimental study to investigate the beneficial effect of geogrid on settlement of soil surface, subjected to repeated loads to simulate the vehicle loading. They reported that settlement of soil surface can be reduced significantly by using geogrid reinforcement.
In designing a machine foundation the coefficient of elastic uniform compression of soil (C_u) is the most important parameter to be determining which can calculate by a cyclic-foundation-load test. Nevertheless, this has not been comprehensively investigated. This paper attempts to study a point of this phenomenon. In the current research, a series of different tests on square footing subjected to static and incremental cyclic loads (similar to cyclic-plate-load test) are performed. The testing program is planned to evaluate the role of sand relative density factor of 45%, 63%, and 78% (D_r) on the coefficient of elastic uniform compression (C_u). Finally, the numerical analysis is simulated the cyclic behavior of footing by the FLAC^{3D}. The results show that the numerical results are in good agreement with experimental results.

2- EXPERIMENTAL STUDY

2.1. Test Equipment

The tests were performed in a tank with a length of 650 mm, width of 650 mm and height of 600 mm. The rigidity of tank has been guaranteed by using four rigid steel plates of 10 mm thickness, in the sides and bottom of the tank and its front face has been consisted of a plexy glass 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 that developed by Koulbuzewski (1948) which was known as the raining technique. 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.

Data acquisition system was developed in such a way so that all stresses and strains could be read and recorded automatically. The system was able to read the data from sixteen channels simultaneously. A S-shape load cell with an accuracy of ±0.01% full scale was also used and placed between the loading shaft and footing with capacity of 1500 kg to precisely measure the pattern of the applied load on the trench surface. Two linear variable differential transducers (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 insure an accurate reading, all of the devices were calibrated prior to each test. The general view of the testing apparatus is shown in Fig. 1.

Figure 1 The general view of the testing apparatus

2.2. Soil

The soil used in this study was a relatively uniform silica sand of grains size between 0.07 and 1.24 mm, D_{50}=0.64 mm, C_c=1.29, C_u=1.51 and G_s=2.67. The maximum and minimum porosities of this sand measured by the raining method were obtained 1.12 and 0.55, respectively. The grain size distribution of this sand is also shown in Fig. 2. In order to study the effect of the soil density on the coefficient of elastic uniform compression of soil (C_u) of footing on the soil, three different relative densities: 45% (relatively loose), 63% (medium dense), and 78% (dense) were selected. These relative densities were achieved in the test tank using sand raining technique by changing perforated plates and height of fall.

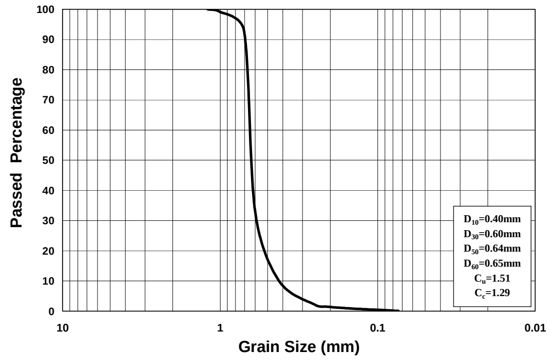


Figure 2 Particle size distribution curve.

2.3. Preparation of Model Test

In order to provide full control condition and repeatability of the tests, uniform sand should be used as the trench. Hence, to approach this situation the raining method was used to prepare the soil in the test tank. Before using the hopper for depositing the soil in the tank, the raining device was calibrated using different heights of pouring and different perforated plates. Consequently, 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.

A square rigid steel plate measuring 100 mm in width and 20 mm in thickness are used as footing. The base of the footings 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 LVDT were placed on the footing model accurately to measure the settlement of footing during loading. Also in order to provide vertical loading alignment, a small semispherical indentation was made at the center of the footing model. The bottom of this was made rough by covering it with epoxy glue and rolling it in sand.

2.4. Testing Program

Some 18 tests in different series were planned and carried out in this research to study the effect of relative density of sand (Dr) on the behavior footing and coefficient of elastic uniform compression of soil (Cu). The details of tests scheme are listed in Table 1. Out of these 18 tests, nine tests were repeated carefully to examine the performance of the apparatus, the accuracy of the measurements and the repeatability of the system. On the other hand all of the tests were repeated twice to verify the repeatability and consistency of the test data. The same pattern of load-settlement relationship with difference of 8% were obtained which shows that the developed procedure and technique produce repeatable tests within the bounds that may be expected from testing geotechnical apparatuses. Also the static and cyclic load applied on the foundation at the rate of 1 kg per second.

Table 1 Scheme of tests

Test Series	D_r (%)	Aim of Tests	No. of Tests
Static tests in small cubic box of 200*200*200 mm	45, 63 and 78	Calibration of numerical model	3+3
Static tests in large box of 650*650*600 mm	45, 63 and 78	Verification of numerical model	3+3
Cyclic tests in cubic box of 650*650*600 mm	45, 63 and 78	Estimation of C_u and Verification of numerical model	3+3

2.5. Pattern of Cyclic Loadings

The history of cyclic loading on footing is selected based on the cyclic plate loading test. Fig. 3 shows the typical time history of incremental cyclic load to apply on footing which applied on the footing at the rate of 1 kg per second. As can be seen, the first increment cyclic is kept constant for sometimes 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 cylices of incremental loading, unloading and reloading are continued until the estimated ultimate has been reached. The magnitude of the load increment is such that the ultimate load is reached in five increments.

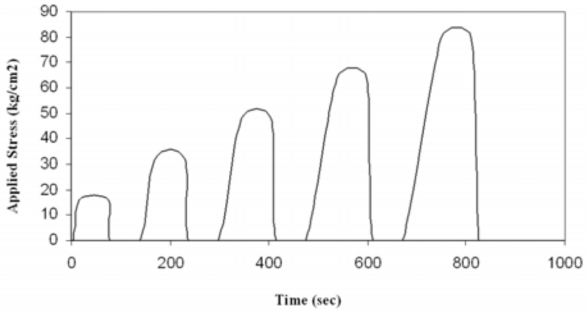


Fig. 3. Typical history of cyclic load on footing.

2.6. Results of Tests

Fig. 4a-b shows the variations of applied static stress with settlement for different soil relative densities. From this figure, the key role of the soil density on bearing capacity pressure and settlement of footing are quite evident. It shows that for a certain applied pressure on the footing the settlement increases when the sand relative density decreases. This is as would be expected because when the density of soil decreases, the footing can only accommodate a limit shear strain before failure. Regardless of the difference in footing settlement, the maximum bearing capacity enhances when the relative density increases.

Fig. 4c shows the variations of applied incremental cyclic load with settlement for different soil relative densities. From this figure, the key role of the soil density on the reduction of settlement is quite evident. It is clear that the value of settlement in each cyclic decrease due to increase in the relative density.

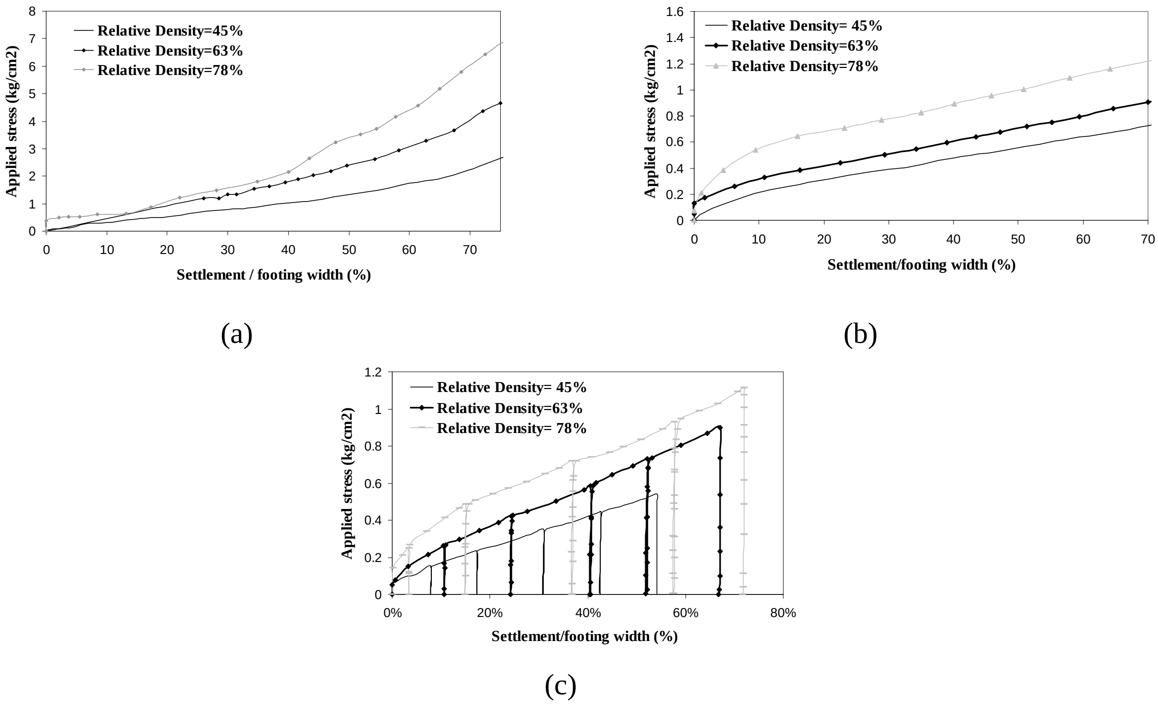


Figure 4 Variations of applied stress with settlement for different soil relative densities (a) static load on small cubic box; (b) static load on large box and (c) incremental cyclic load on large box

The elastic rebound of the footing corresponding to each intensity is shown in Fig. 5. It states that the slope of elastic lines increase with increasing the relative density of sand. Fig. 6 shows the variation of coefficient of elastic uniform, C_u with relative density of sand. From this figure, the key role of the soil density on C_u of footing is quite evident. It is clear that the percent increase in Cu for variation of relative density between 63% and 78% is substantially greater than those for relative densities between 45% and 63%. The loose relative density is similar to low stiffness of sand while the dense relative density is correspond to high stiffness of sand beneath the footing.

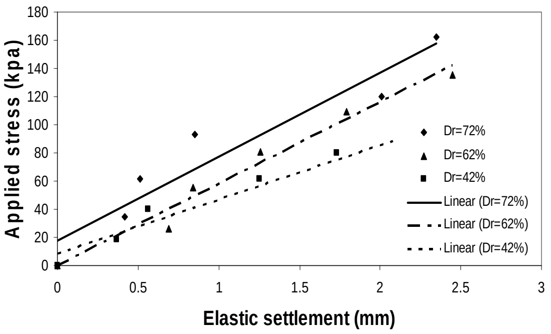


Figure 5 Variation of applied stress with elastic settlement

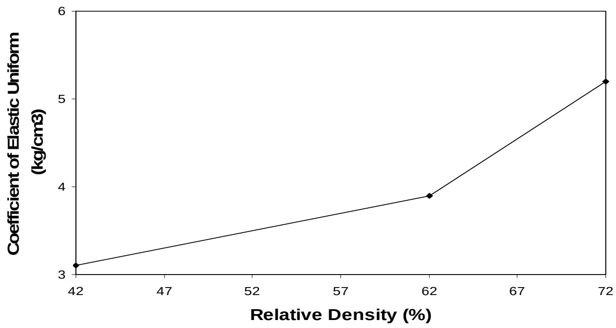
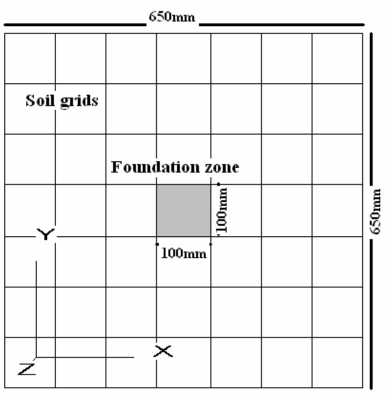


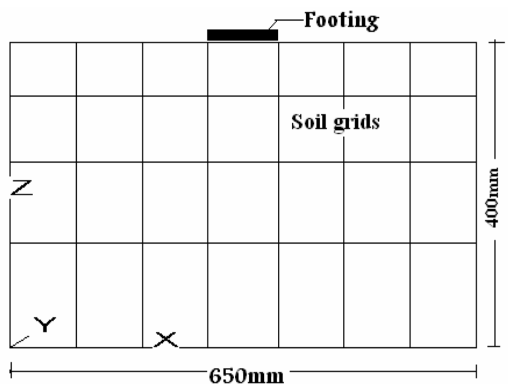
Figure 6 Variation of coefficient of elastic uniform C_u with relative density of sand

3. NUMERICAL ANALYSIS PROCEDURE

We used the finite difference program FLAC^{3D} (Itasca Group, 1997) to model square interfering footings constructed on sand. The Mohr–Coulomb failure criterion was used for soil behavior. The rigid rough footing used in this numerical study had a square shape of 100*100 mm in plan view. The model of cubical soil grid with dimensions of 650*650 mm in plan and 400 mm in height was used to construct of the 3D media coincide to experimental model (Fig. 1). In all analyses conducted in the present study, footing is located on the ground surface and the soil is cohesionless. Frydman and Burd (1997) used FLAC and showed that a change in the velocity applied on footing nodes and zone dimension has a great effect on the behavior of footing and soil. Analyses were performed under controlled displacement. Rigidity of the footing was simulated by applying an equal displacement vector in the vertical direction on all soil nodes below the footing. Roughness of the footing was simulated by providing lateral resistance at the footing–soil interface. Therefore, soil–footing contact nodes are constrained in both horizontal directions (x and y), and they move only in the vertical (z) direction. The mesh shape in plan and view elevation for FLAC analysis based on the dimension of experimental model test is shown in Fig. 7.



(a)



(b)

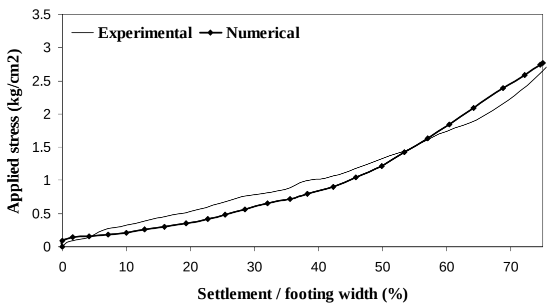
Figure 7 Finite difference mesh for FLAC analyses (a) mesh shape in plan and (b) view elevation

3.1. Calibration of Numerical Model

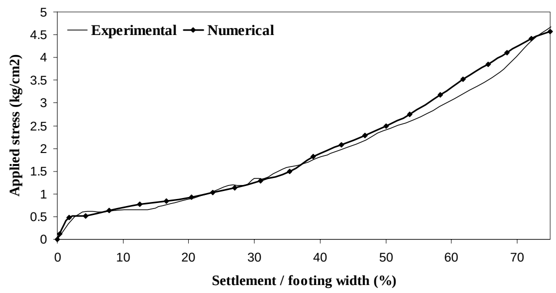
A granular soil (SP) is used in experimental tests, hence the parameters used in FLAC^{3D} analyses are ν, E, ψ, ϕ and γ_d stand for poison ratio, elastic modulus, dilation angle, friction angle and dry soil density, respectively. The material properties obtained of calibrating for the numerical modeling and experimental results of small cubic box of 200*200*200 mm under static loads are given in Tables 2 and also the results obtained from tests and numerical analyses are compared in Figs. 8. The results reveal that the predictions of numerical analyses are reasonable. Also, the variation range of dilation angle in Table 2 confirms that the dilation angle has a significant influence on the numerical estimation of the bearing capacity (Yin et al. (2001), Erickson and Drescher (2002), Frydman and Burd (1997), DeBorst and Vermeer (1984)).

Table 2 Mechanical properties of soil in numerical model obtained of calibration

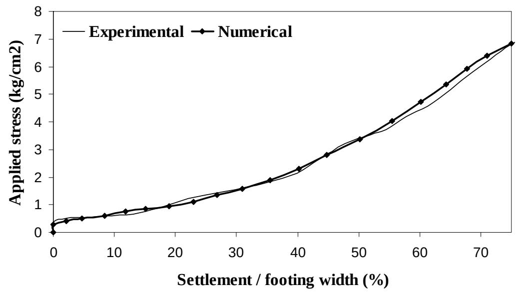
Parameter series	ν	E (Mpa)	ψ (Degree)	ϕ (Degree)	γ_d (kN/m^3)
sand with relative density of 45%	0.32	11	3	30	14.30
sand with relative density of 57%	0.32	13	12	32	15.20
sand with relative density of 62%	0.32	15	20	34	17.25



(a)



(b)

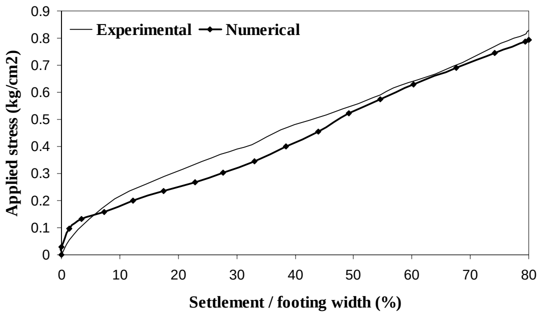


(c)

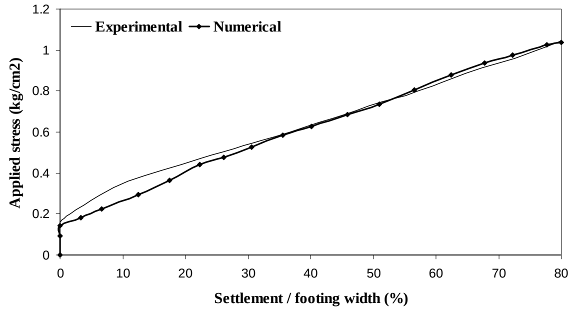
Figure 8 Calibration for square footing of 50*50 mm on sand in small box of 200*200*200 mm: (a) D_r=45%; (b) D_r=63% and (c) D_r=78%

3.2. Verification of Numerical Model

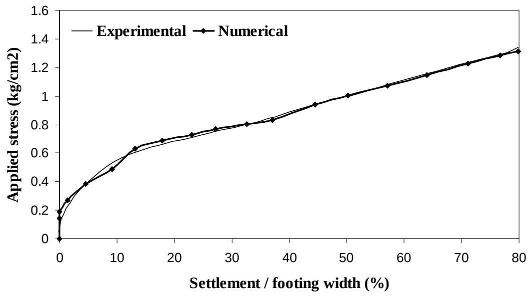
In this section, the accuracy of the used numerical model for both static and cyclic laboratory tests is verified. To achieve this, six numbers of numerical analyses on footing under static and cyclic loading tests are performed, and compared the results with those of the above-mentioned experiments (Fig. 4a and 4b). The material properties for the numerical modeling have already been defined in Tables 2. The results obtained from tests and numerical analyses are compared in Fig. 9 and Fig. 10. The results reveal that the maximum difference between tests results and numerical analysis is less than 10% and the predictions of numerical analyses are reasonable in range of geotechnical problems.



(a)

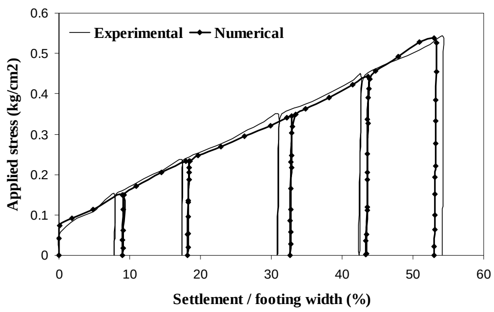


(b)

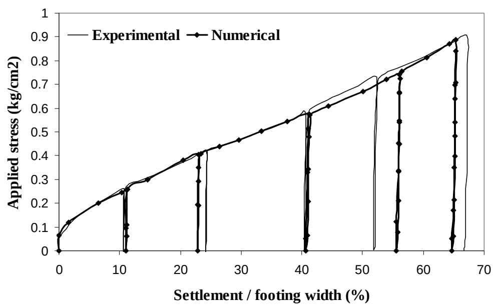


(c)

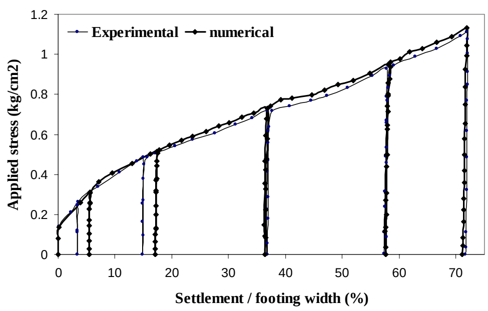
Figure 9 Verification for square footing of 100*100 mm on sand in large box of 650*650*400 mm under static load: (a) D_r=45%; (b) D_r=63% and (c) D_r=78%



(a)



(b)



(c)

Figure 10 Verification for square footing of 100*100 mm: on sand in large box of 650*650*400 mm under cyclic load: (a) D_r=45%; (b) D_r=63% and (c) D_r=78%

4. CONCLUSION

Laboratory tests and numerical analyses based on FLAC were performed to investigate the behavior of square footing constructed on the surface of homogeneous sand under static and cyclic loads. In numerical analyses the behavior of the sand was controlled using the Mohr–Coulomb criterion and a nonassociated flow rule. The laboratory tests and numerical analyses revealed that the behavior of footing is affected by the sand relative density significantly. The variation of coefficient of elastic uniform C_u of footing for variation of relative density between 63% and 78% is substantially greater than those for relative densities between 45% and 63%. Also the used numerical model could predict the behavior of footing and sand as well as laboratory tests. The results reveal that the maximum difference between tests and numerical results is not greater than 10% and the results of numerical analyses are in good agreement with experimental results.

REFERENCES

DeBorst, R., Vermeer, P.A. (1984). Possibilities and limitations of finite elements for limit analysis. *Geotechnique* **34: 2**, 199–210.

DeMerchant, M.R. (2002). Plate load tests on geogrid-reinforced expanded shale lightweight aggregate. Geotextile and Geomembranes **20: 2**, 173-190.

Erickson, H.L., Drescher, A. (2002). Bearing capacity of circular footings. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **128: 1,** 38–43.

Frydman, S., Burd, H.J. (1997). Numerical studies of bearing capacity factor Ng. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **123: 1,** 20–29.

Kolbuzewski, J. (1948) An experimental study on the maximum and minimum porosities of sands, *Proc. of the 2nd International Conference on Soil Mechanics and Foundation Engineering Rotterdam*, **vol. I:** 158-165.,

Moghaddas Tafreshi, S.N., Khalaj, O. (2008). Laboratory tests of small-diameter HDPE pipes buried in reinforced sand under repeated load. *Geotextiles and Geomembranes* 26: 8, 145-163

Shvets. N. S., Nazha. P. N. (2000). Elastic coefficients of anisotropic foundation beds. *Journal of Soil Mechanics and Foundation Engineering, springerlink* **37: 2,** 29-34.

Yin, J.H., Wang, Y.J., Selvadurai, A.P.S., 2001. Influence of nonassociativity on the bearing capacity of a strip footing. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **127: 11,** 985–989.