Geomechanics and Engineering, *Vol. 8*, *No. 2* (*2015*) *221-235*
DOI: http://dx.doi.org/10.12989/gae.2015.8.2.221

Experimental investigation of the effects of pipe location on the bearing capacity

Selçuk Bildik *[1] and Mustafa Laman [2]

[1] *Department of Civil Engineering, Osmaniye Korkut Ata University, Osmaniye, 80000, Turkey*
[2] *Department of Civil Engineering, Cukurova University, Adana, 01330, Turkey*

(*Received August 18, 2014, Revised November 14, 2014, Accepted November 15, 2014*)

Abstract. A series of laboratory model tests were conducted to investigate the effects of buried pipes location on the bearing capacity of strip footing in cohesionless soil. The variables examined in the testing program include relative density of the sand, loading rate of tests, burial depths of pipe and horizontal distance of pipe to footing. The test results showed a significant increase in bearing capacities when embedment ratio of pipe and horizontal distance of pipe to footing were increased. Based on the test results, it can be concluded that the location of pipes and relative density of sand are main parameters that affect the bearing capacity of strip footing. However, loading rate has not considerable effect on bearing capacity.

Keywords: embedment ratio; loading rate; pipes; bearing capacity; laboratory tests

1. Introduction

Buried pipes are generally designed to withstand construction loads, dead loads and any dynamic loads that may be imposed upon it during its lifetime. The soil-pipe interaction problems have been discussed since early 20th century. There have been a lot of studies recently about buried pipes such as Balkaya *et al*. (2013), Khatri *et al*. (2013), Sun *et al*. (2013), Corey *et al*. (2014). The first known study about buried pipe was conducted by Marston in 1913. In this study, Marston determined the loads acting on the pipe crown. Marston's theory was developed considering the Terzaghi's theory. The important parameter in determining the loads applied to the pipe crown is settlement differences between backfill and natural soil. In 1941, Spangler investigated the effects of the surrounding soil on the flexible pipe's deflection. Spangler's study showed that pipe stiffness and soil are major parameters for determining the lateral deformation of pipe under loads. Burns and Richard (1964) developed a numerical method and in their method the trench medium was considered as full elastic and the applied loads were converted to lateral loads by using Poisson Ratio. The results of this method did not show a good agreement for small-diameter and thick-walled pipes. Hoeg (1966) developed a new elastic solution for deflection of an elastic pipe placed in an infinite elastic media. Additional to the theoretical studies, in the literature many researchers have carried out experimental studies about buried pipes. Hurd

∗Corresponding author, Assistant Professor, *Dr*., E-mail: selcukbildik65@gmail.com
[a] Professor, *Dr*., E-mail: mlaman@cu.edu.tr

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

(1986) was investigated long term behavior of different polyurethane pipes with field tests. Experiments have shown that pipe deformations are not proportional to the pipe diameter but deformations are related to pipe flexibility factor. In 1989, Adams *et al*. (1989) investigated strain behavior of pipe during filling stage with field tests. This study showed that horizontal strains of pipe were smaller than vertical strains of pipe at short-time loadings. In literature many researchers have carried out laboratory tests about buried pipes such as Selig *et al*. (1993), Branchman (1999), Cho (2003), Cameron (2005), Terzi (2007) and Talesnick *et al*. (2011). In these experimental studies, researchers focused on load-displacement behavior of pipes under cellular loads and researchers emphasized pipe behavior. In literature, there are limited studies about taking into pipe-soil interaction problem in terms of bearing capacity (Branchman and Krushelnitzky 2005, Terzi 2007). In this study, the behavior of pipes embedded in sand was investigated with series of laboratory tests. The variables examined in the testing program include relative density of the sand, burial depths of pipe and horizontal distance of pipe to footing. The most important difference between the literature and this study is that investigation of the effect of the horizontal location of pipe on bearing capacity of strips footing and the behavior of the pipe and the footing are discussed together. In addition to these parameters, experimental setup effect such as loading rate is examined.

2. Testing facility

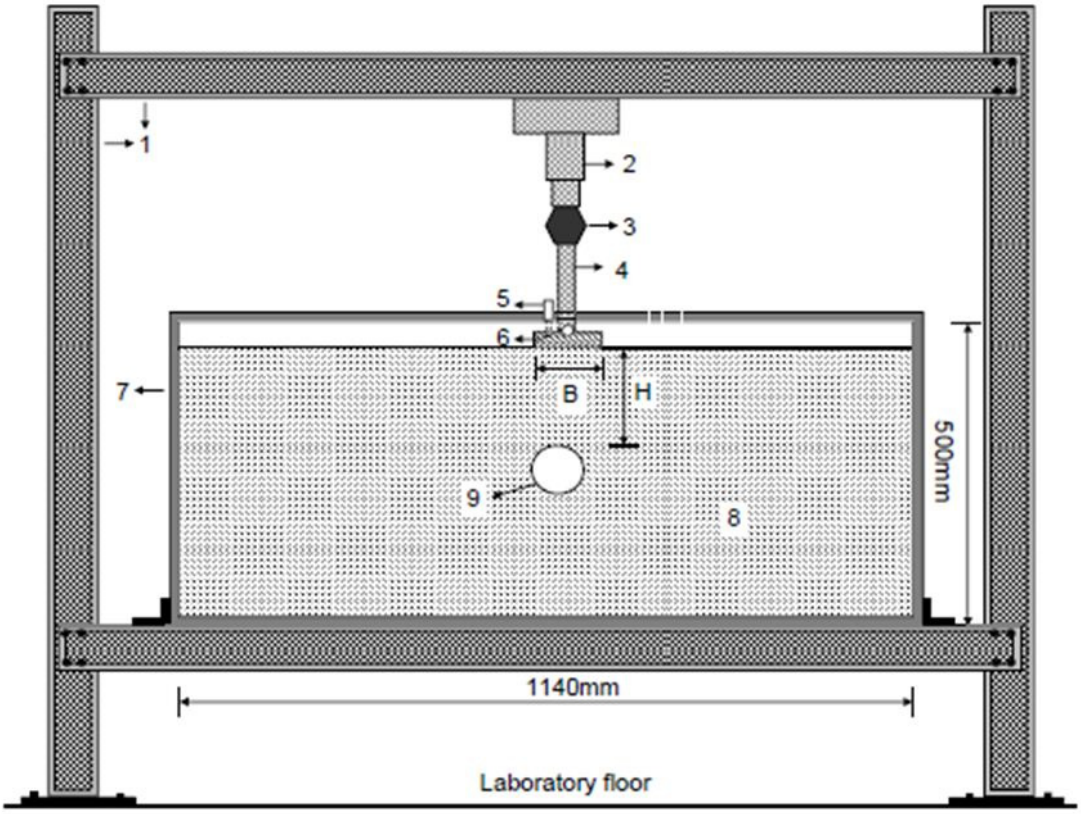
The experimental program was performed using the facility in the Geotechnical Laboratory of the Civil Engineering Department of the University of Cukurova. The testing facility consists of three main parts, namely the loading system, the test box and the data acquisition system. The facility and a typical test model are schematically shown in Fig. 1 (Bildik 2013).

2.1 Loading system

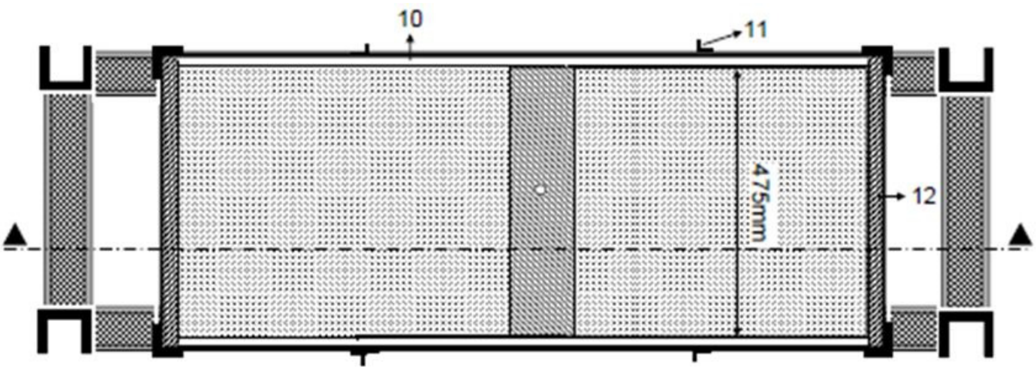
The loading system consists of the loading frame, the motor controlled hydraulic jack system and control unit. The loading frame comprises of four vertical rods and these rods tied with four horizontal profiles from bottom and top. The distance between the frame edge struts is 4.6 meters. The loading frame width is 0.6 meter and the height is 2.4 meter. Static vertical loads were applied to the model footing by hydraulic jack system. The hydraulic jack system attached to the loading frame located above the test box. The vertical static loads with different hertz and speed can be produced and controlled by a hydraulic jack system. The applied loading rate was between 1 to 9 mm/min. The control unit consists of an electronic remote control which regulates loading rate and direction.

2.2 Test boxt

In this study a series of laboratory tests were performed in a testing tank which provides the plane strain condition. The dimensions of the test box have been investigated by numerically to determine the boundary effects. Hence, the testing tank is designed as a steel frame with inside dimensions of 1.140 m (length), 0.475 m (width) and 0.500 m (depth) as shown in Fig. 2. The two sidewalls of test box are made of 10 mm thick glass to see the sand sample during preparation and observe the sand particle deformations during the tests. The other surfaces of test box were made



(a)



(b)

1. Loading frame
2. Hydraulic jacks with engine controls
3. Loadcell
4. Loading cap
5. Displacement transducer
6. Model foundation
7. Steel profile
8. Model soil
9. Model pipe
10. Glass sheets
11. Reinforcement profile
12. Wooden sheets

Fig. 1 The schematic representation of the testing facility

Fig. 2 The test box

of 25 mm thick wood. The inside walls were polished to minimize friction between the inside walls of test box and the sand.

2.3 Data acquisition system

TDS-530 data acquisition system was used in the tests and this system was able to read the data from 30 channels and recorded automatically. An electronic 25 kN capacity load cell was used to measure applied loads. Settlements were measured using two linear variable displacement transducers (LVDTs) with an accuracy of 0.01% of full range (50 mm). They were placed on the two sides of the footing. The applied loads and vertical displacements were measured by data acquisition system.

3. Laboratory tests

The main objective of this study is to investigate the effect of location of footing against the pipe on bearing capacity in sand. The test program and materials used in the tests are described below.

3.1 Model ground

The soil used for the model tests was uniform, clean and fine sand obtained from Seyhan River bed. The grain size distribution of sand is shown in Fig. 3. The sand class is poorly graded sand (SP) in the Unified Soil Classification System. The maximum and minimum dry densities of the sand were determined using ASTM D4253 and D4254. The specific gravity of sand was determined by picnometer test and Table 1 summarizes the general physical characteristics of the sand.

3.2 Pipe

The pipe diameters vary a wide range used for different purposes such as drainage, sewer, and petroleum systems, etc. The plastic pipes used in the tests had 75 mm external diameter, 2.2 mm

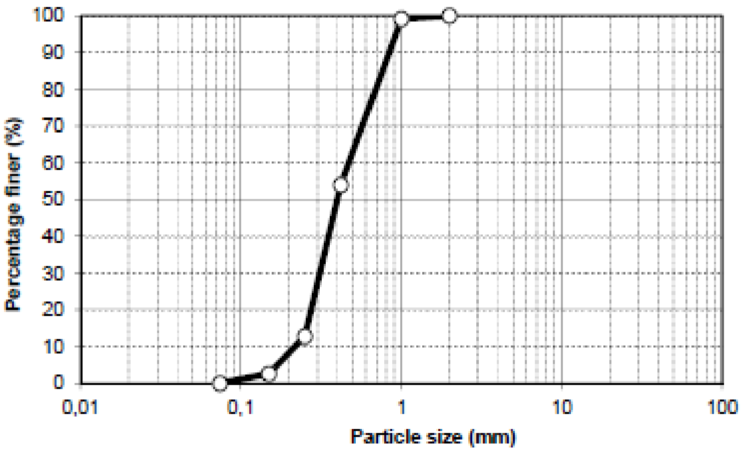


Fig. 3 Grain size distribution of sand

Table 1 Properties of sand

Property	Value
Coarse sand fraction (%)	0.0
Medium sand fraction (%)	46.9
Fine sand fraction (%)	54.1
D_{10} (mm)	0.20
D_{30} (mm)	0.30
D_{60} (mm)	0.50
Uniformity coefficient, C_u	2.78
Coefficient of curvature, C_c	1.00
Specific gravity, γ (kN/m^3)	26.8
Maximum dry unit weight, γ_{dmax} (kN/m^3)	17.3
Minimum dry unit weight γ_{dmin} (kN/m^3)	14.4
Classification (*USCS*)	SP

thickness and 470 mm length. The length of the pipe is 0.5 cm shorter than the width of the tank and the two ends of the pipe was clogged with foam to block sand.

3.3 Preparation of the model tests

To obtain a homogeneous sand bed in the experimental study, the same compaction procedure was used to fill sand in 50 mm thick layer into to the test box. In this method the sand layer was first weighed and placed in the box for 50mm thick layer and compacted by a hand-held vibratory compactor. The average unit weights of sand in the experimental studies were 15.30 and 16.30 kN/m^3. Corresponding relative densities of the sand samples were 35 and 65%, respectively. The value of internal friction angles of the sand was determined from both direct shear tests and tri-axial tests as 39 and 41.5°, respectively. Pipe was placed to desired location in sand bed and

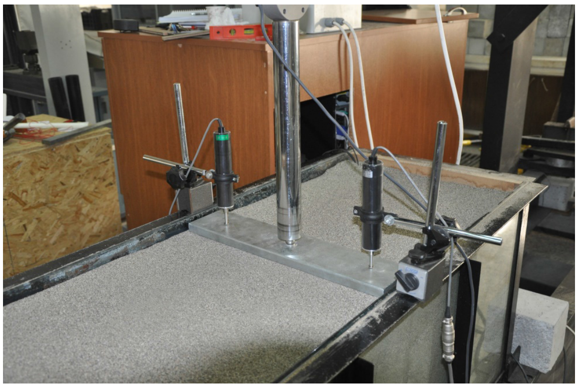


Fig. 4 The test setup

loading tests were carried out on rigid model strip footing fabricated from mild steel. It was 100 mm in width, 465 mm in length and 20 mm in thickness. The load is applied to the model footings through a bearing ball to prevent any moment transfer from the loading system. The test setup was shown in Fig. 4.

3.4 Test program

A total of 44 model tests in different series were planned and carried out in this study to investigate the effects of the variable parameters such as relative density of sand (*Dr*), loading rate (LR), embedment ratio of pipe (H/D), and horizontal distance of pipe to footing (*x*/*D*). The investigated parameters were described in Fig. 5. The test programs with constant and variable parameters used were summarized in Table 2. Some tests were repeated at least twice to verify the consistency of the test data. 9 tests were conducted in 2 series.

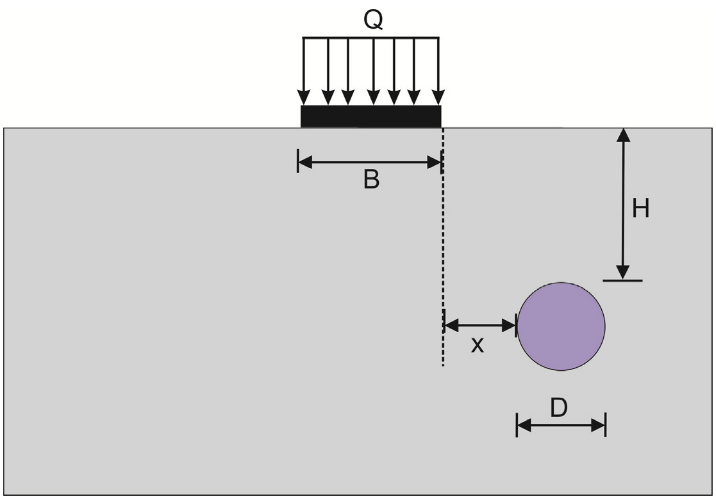


Fig. 5 The parameters investigated

Table 2 Model test program

Series	Tests	Constant parameters	Variable parameters
-	1	without pipes, *Dr* = 35%	LR = 0.94-3.76-5.64-9.41 mm/min
1	2	LR = 0.94 mm/min, pipe at center of footing, *Dr* = 35%	H/D = 1-2-3-4-5
1	3	LR = 0.94 mm/min, pipe at center of footing, *Dr* = 65%	H/D = 1-2-3-4-5
2	4	LR = 0.94 mm/min, H/D = 1, *Dr* = 35%	*x*/*D* = 0-1-2-3-4
2	5	LR = 0.94 mm/min, H/D = 2, *Dr* = 35%	*x*/*D* = 0-1-2-3-4
2	6	LR = 0.94 mm/min, H/D = 3, *Dr* = 35%	*x*/*D* = 0-1-2-3-4
2	7	LR = 0.94 mm/min, H/D = 4, *Dr* = 35%	*x*/*D* = 0-1-2-3-4
2	8	LR = 0.94 mm/min, H/D = 5, *Dr* = 35%	*x*/*D* = 0-1-2-3-4
2	9	LR = 0.94 mm/min, H/D = 3, *Dr* = 65%	*x*/*D* = 0-1-2-3-4

4. Results and discussion

In this section a total of 44 model test results are presented and the effects of different parameters are discussed. The bearing capacity behavior of the footing is represented using a non-dimensional factor, called bearing capacity ratio, BCR. This factor is defined as the ratio of the bearing capacity of footing with pipe (q_{pipe}) to the ultimate bearing capacity of footing without pipe (q_u).

$$BCR = \frac{q_{pipe}}{q_u} \tag{1}$$

The footing settlement (s) is also expressed in non-dimensional form in terms of the footing width, B as the ratio s/B (%). The ultimate bearing capacities for the model are determined from the load-displacement curves as the pronounced peaks, after which the footing collapses and the load decreases.

4.1 Effect of loading rate on bearing capacity

In this series of tests, the effect of loading rate was investigated on bearing capacity. For this purpose four tests were carried out in four different loading rates. Four different loading rates were 0.94 mm/min, 3.76 mm/min, 5.64 mm/min and 9.41 mm/min. In the tests, the relative density of sand was 35% and the model ground was without pipe. Load settlement curves for four different loading rates obtained from model tests are presented in Fig. 6. The bearing capacity values depending on the loading rate are shown in Fig. 7. The ultimate bearing capacity increased 4% with the loading rate is increased from 0.94 mm/min to 9.41 mm/min. The test results are shown that the loading rate has not considerable effect on bearing capacity. The loading rate is chosen as an average value of 3.76 mm/min for other tests.

4.2 Effect of the embedment ratio of pipe

A series of tests was performed on strip footing resting on cohesionless soil in order to investigate the effect of the embedment ratio of pipe on bearing capacity. The tests were carried

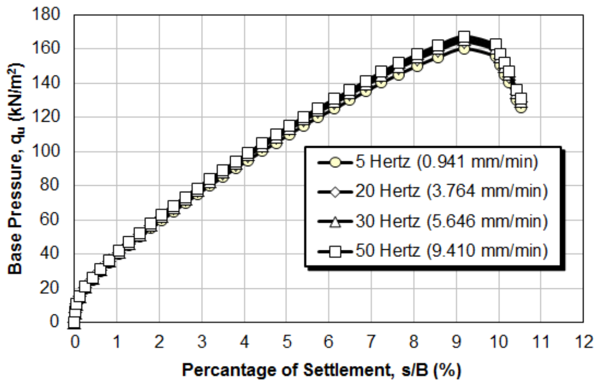


Fig. 6 Variations of *q* with s/B for model tests with different loading rates

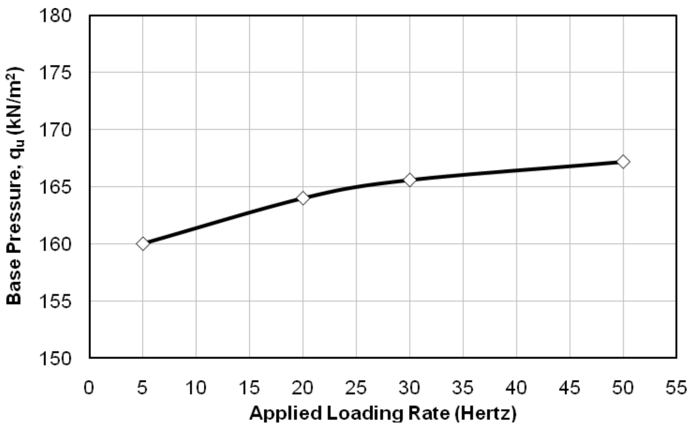


Fig. 7 Variations of bearing capacity with loading rates

out with two different relative densities of sand. Corresponding relative densities of the sand samples were 35 and 65%, respectively. Tests were also conducted with the strip footing on cohesionless soil without pipe for the purpose of comparison.

4.2.1 Test results for relative density of 35%

These series of tests were performed on strip footing resting on a cohesionless soil, in order to investigate the effect of embedment ratio of the pipe (H/D) in soil with a relative density of 35%. The ratio of the diameter of pipe (D) and the widths of the footing (B) were D/B = 0.75 and this value was constant in all tests. Tests were conducted for H/D ratios of 1 to 5 and pipe was located at the center of the footing profile. Load settlement curves for five different embedment ratios obtained from model tests are presented in Fig. 8. Additionally, the test results are presented in Fig. 9 in the form of the BCR which are obtained as the ultimate values of load-settlement curves of Fig. 8. The results indicate that, the ultimate bearing capacity increases significantly with increasing depth of the pipe from the strip footing level. When the pipe is moving away from the embedment ratio of H/D = 1 to the embedment ratio of H/D = 2, there is a serious increase in bearing capacity (an average value of 20%). The increment in bearing capacity is 85% for H/D = 3.

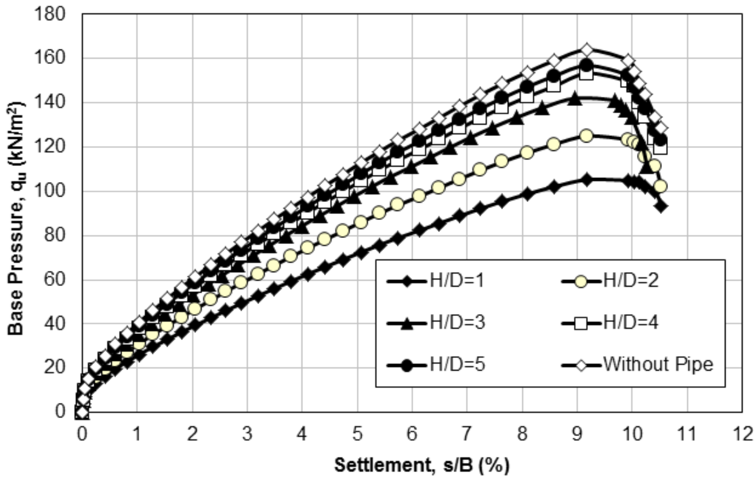


Fig. 8 Load – settlement curves for different embedment ratios (*Dr* = 35%)

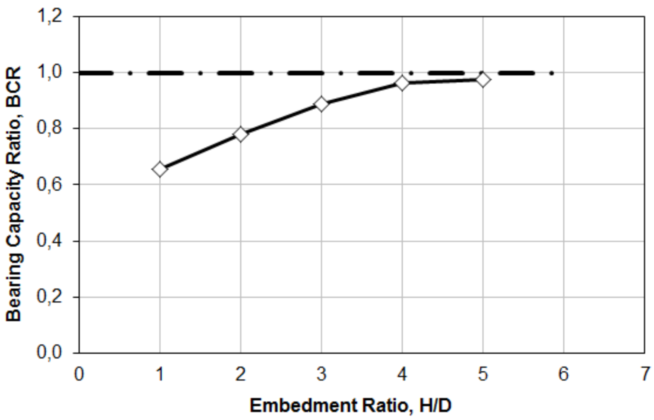


Fig. 9 Variation of BCR with H/D (*Dr* = 35%)

However, the rate of increment in bearing capacity decreases with increasing embedment ratio of pipe until H/D = 5. So, the ultimate bearing capacity is equal to the case of without pipes and it means that the effect of pipe is minimized when the pipe is placed at an embedment ratio five times the pipe diameter. The effect of pipe embedment ratio can be explained that when the pipe moves away from the stress zone, the bearing capacity increases. In addition to that, the thickness of homogenous zone between pipe and footing was efficient and the ultimate bearing capacity increases with increasing thickness of homogenous zoned.

4.2.2 Test results for relative density of 65%

These series of tests were performed on strip footing resting on a cohesionless soil, in order to investigate the effect of embedment ratio of the pipe (H/D) in soil with a relative density of 65%. The ratio of the diameter of pipe (D) and the widths of the footing (B) were D/B = 0.75 and this value was constant in all tests. Tests were conducted for H/D ratios of 1 to 5 and pipe was located

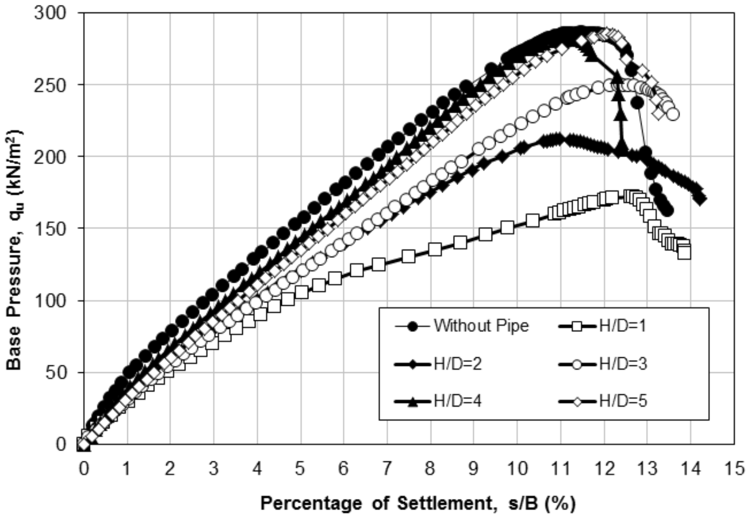


Fig. 10 Load – settlement curves for different embedment ratios (*Dr* = 65%)

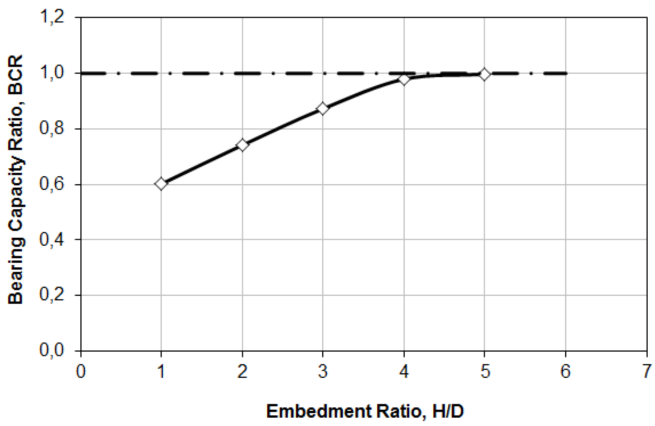


Fig. 11 Variation of BCR with H/D (*Dr* = 65%)

at center of the footing profile. Load-settlement curves for five different embedment ratios obtained from model tests are presented in Fig. 10 and the test results are presented in Fig. 11 in the form of the BCR. The test results show moreless similar trend with the results of relative density of 35%. The ultimate bearing capacity increases significantly with increasing depth of the pipe from the strip footing. When the pipe is moving away from the embedment ratio of H/D = 1 to the embedment ratio of H/D = 2, there is a serious increase in bearing capacity (an average value of 20%). The increment bearing capacity is 88% for H/D = 3. However, the rate of increment in bearing capacity decreases with increasing embedment ratio of pipe until H/D = 5. So, the ultimate bearing capacity is equal to the case of without pipes and it means that the effect of pipe is minimized when the pipe is placed at an embedment ratio five times the pipe diameter. The effect of pipe embedment ratio can be explained that when the pipe moves away from the stress zone, the bearing capacity increases. In addition to that, the thickness of homogenous zone between pipe and footing was efficient and the ultimate bearing capacity increases with increasing thickness of homogenous zone.

4.3 Effect of the horizontal distance of pipe to footing

In addition to the series of model tests mentioned above for pipes located at the center of footing, second series of model tests were carried out for different horizontal distances of pipe to footing. The effect of horizontal distance of pipe to footing on the bearing capacity was investigated for two different densities of sand at second series of tests. Tests were also conducted with the strip footing on cohesionless soil without pipe for the purpose of comparison.

4.3.1 Test results for relative density of 35%

The second series of tests were performed on strip footing resting on a cohesionless soil in order to investigate the effect of horizontal distance of the pipe (x/D) to footing in soil with a relative density of 35%. The ratio of the diameter of pipe (D) and the widths of the footing (B) were D/B = 0.75 and this value was constant in all tests. Tests were conducted for H/D ratios of 1 to 5 and pipe was located at different distances (x/D) of 0 to 4. The typical load settlement curves for H/D = 3 are shown in Fig. 12 and the results are presented in the form of BCR in Fig. 13. The results show that the ultimate bearing capacity increases significantly with increasing horizontal distance of the pipe from the strip footing. When the pipe is moving away at a ratio of x/D = 4 in the horizontal direction from the footing, there is a significant increase in bearing capacity and the bearing capacity reaches a value of 99% of the case of without pipe. This case can be explained as, when the pipe moves away from the stress zone, the bearing capacity increases.

4.3.2 Test results for relative density of 65%

These series of tests were performed on strip footing resting on a cohesionless soil, in order to investigate the effect of horizontal distance of the pipe (x/D) to footing in soil with a relative

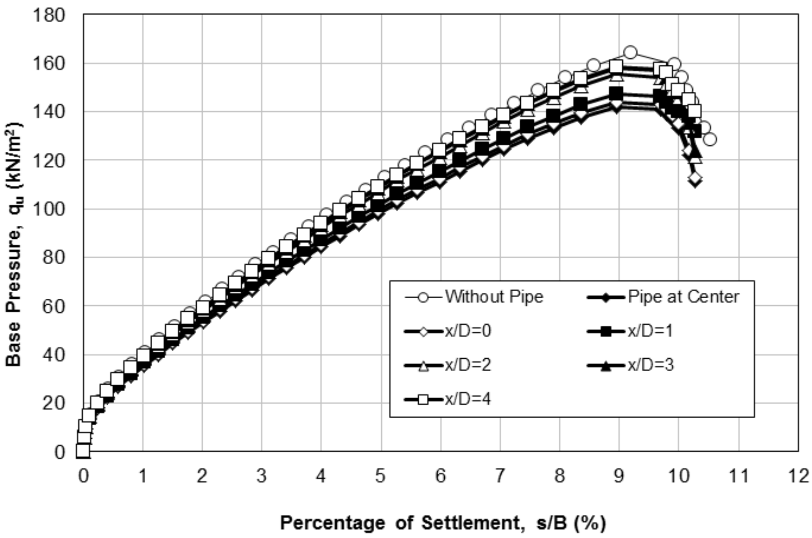


Fig. 12 Load – settlement curves for different horizontal distances (H/D = 3, *Dr* = 35%)

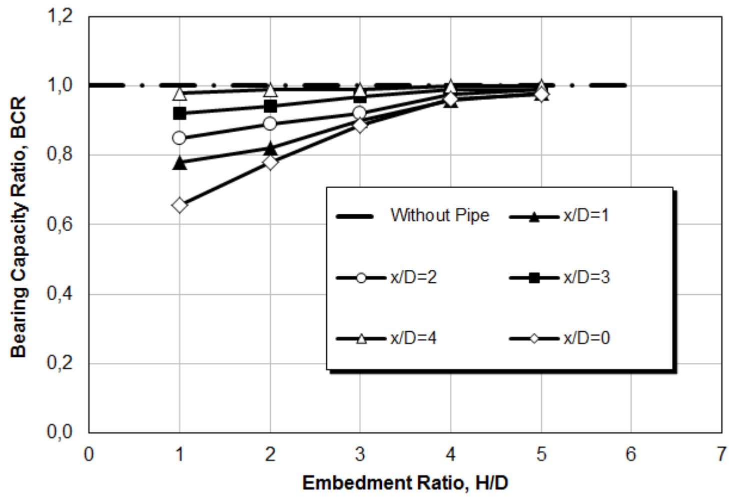


Fig. 13 Variation of BCR with H/D for different *x*/*D* ratios (*Dr* = 35%)

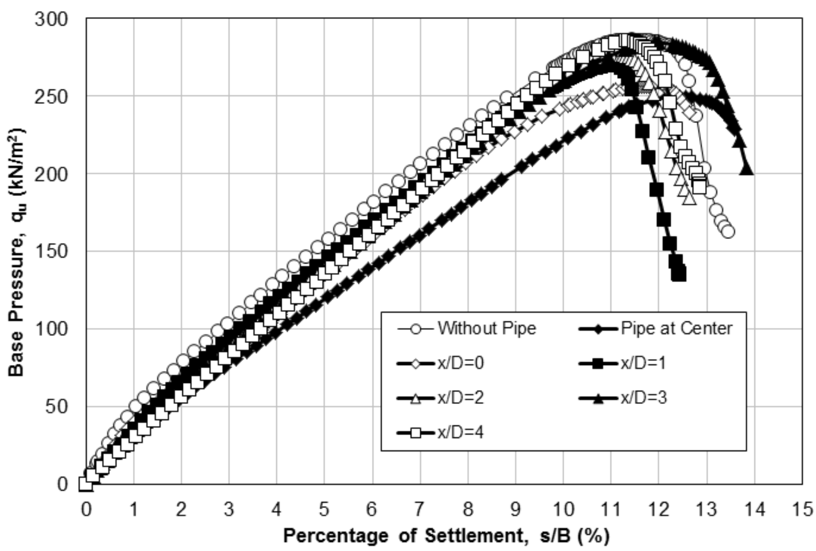


Fig. 14 Load – settlement curves for different horizontal distances (H/D = 3, *Dr* = 65%)

density of 65%. The ratio of the diameter of pipe (D) and the widths of the footing (B) were D/B = 0.75 and this value was constant in all tests. Tests were conducted for H/D = 3 and pipe was located at different distances (*x*/*D*) of 0 to 4. Load settlement curves for five different horizontal distances obtained from model tests are presented in Fig. 14. Additionally, the test results are presented in Fig. 15 in the form of the BCR which are obtained as the ultimate values of load-settlement curves of Fig. 14. The test results show similar trend with the test results for relative density of 35%. The results show that the ultimate bearing capacity increases significantly with increasing horizontal distance of the pipe from the strip footing. When the pipe is moving away at a ratio of *x*/*D* = 4 in the horizontal direction from the footing, there is a significant

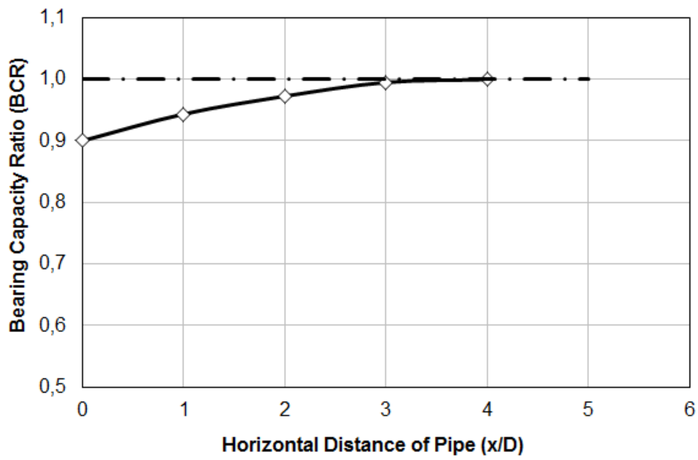


Fig. 15 Variation of BCR with H/D for different *x*/*D* ratios (*Dr* = 65%)

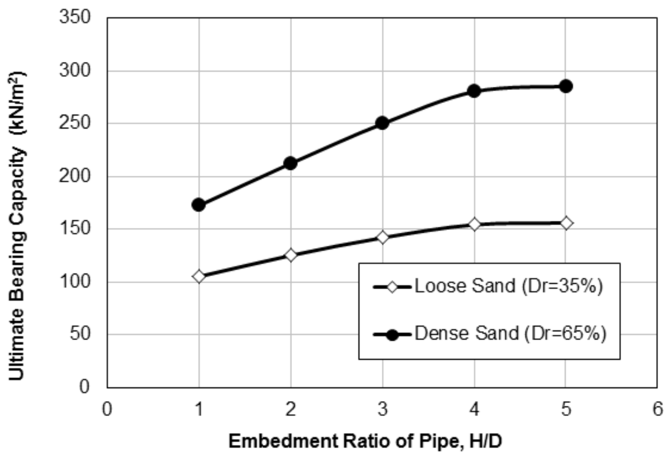


Fig. 16 The effect of relative density for different H/D ratios

increase in bearing capacity and the bearing capacity reaches a value of 99% of the case of without pipe. This case can be explained as, when the pipe moves away from the stress zone, the bearing capacity increases.

4.4 The effect of the relative density on bearing capacity

In this study, the effect of relative density of sand on the bearing capacity of strip footing was investigated. The tests were carried out for D/B value of 0.75 and this value was constant in all tests. The pipe was located at different embedment ratios (H/D) of 1 to 5 for two different relative densities of 35% and 65%. The ultimate bearing capacity of strip footing for different embedment ratios is presented in Fig. 16 for two different relative densities. Fig. 16 clearly shows that the ultimate bearing capacity of the footing is significantly increases with an increase of relative density of sand. The increment is 70% for H/D = 1 and it is 85% for H/D = 5.

5. Limitations

In this study, the model tests were conducted on a small scale model footing, while the sand particles used were with the same dimensions as in the prototype. Therefore, model footing or the soil may not play the same role as in the prototype and it might cause some influence on the model test results. But, this study can be evaluated as a useful basis for further research in which the results of this study can be of support with full-scale loading tests or centrifugal model test studies.

6. Conclusions

Model tests have been carried out to investigate the bearing capacity of strip footing resting on sand with pipe. The study primarily aimed at determining the effect of pipe's location to the footing and its behavior with various relative density of sand. In addition to that the loading rate effect on bearing capacity is investigated. Based on the experimental studies, the following main conclusions can be drawn:

- The results show that the bearing capacity and the bearing capacity ratio (BCR), increase almost linearly with an increase in depth of pipe to width ratio of H/D = 4. Beyond this value, the ultimate bearing capacity remains constant like that of a footing located on sand without pipe.
- The bearing capacity of strip footing with pipe is significantly dependent on the relative density of sand, the embedment ratio of pipe and the horizontal distance of pipe to footing.
- The results indicate that ultimate bearing capacity increases significantly with increasing depth of the pipe from the strip footing level for both relative densities. When the pipe is moving away from the footing level, there is a serious increment in bearing capacity. However, the rate of increment in bearing capacity decreases with increasing embedment ratio of pipe until H/D = 5. So, the ultimate bearing capacity is equal to the case of without pipes and it means that the effect of pipe is minimized when the pipe is placed at an embedment ratio of five times the pipe diameter. The effect of pipe embedment ratio can be explained that when the pipe moves away from the stress zone, the bearing capacity increases. In addition to that, the thickness of homogenous zone between pipe and footing was efficient and the ultimate bearing capacity increases with increasing thickness of homogenous zone.
- In this study, the horizontal distance of pipe to footing was investigated for both relative densities. The results show that the ultimate bearing capacity increases significantly with increasing horizontal distance of the pipe from the strip footing. When the pipe is moving away at a ratio of $x/D = 4$ in the horizontal direction from the footing, there is a significant increment in bearing capacity and the bearing capacity reaches a value of 99% of the case of without pipe. This case can be explained as, when the pipe moves away from the stress zone, the bearing capacity increases.
- A significant increment in footing performance resting on sand can be obtained by increasing the relative density of sand. The results show that the ultimate bearing capacity increment 70% at H/D = 1 and 85% at H/D = 5 for relative densities of both increase 35% and 65%.

Acknowledgments

First author thanks to TUBITAK (The Scientific and Technological Research Council of Turkey) for scholarships financial support.

References

Adams, D.N., Muindi, T. and Selig E.T. (1989), "Polyethylene Pipe under High Fill", Transportation Research Record, No. 1231, pp. 88-95.

ASTM D 4253-00 (2000), Standart Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table.

ASTM D 4254-00 (2000), Standart Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density.

Balkaya, M., Moore, I. and Sağlamer, A. (2013), "Study of non-uniform bedding support under continuous PVC water distribution pipes", *Tunn. Undergr. Space Technol.*, **35**, 99-108.

Bildik, S. (2013), "Investigation of buried pipe systems in different soil and loading conditions", Ph.D. Thesis, Institute of Natural and Applied Science, Cukurova University, Adana, Turkey.

Brachman, R.W.I. (1999), "Structural performance of Leachete collection pipes", Ph.D. Thesis, Department of Civil and Environmental Engineering, University of Western Ontario, London, ON, Canada.

Brachman, R.W.I. and Krushelnitzky, R.P. (2005), "Response of a landfill drainage pipe buried in a trench", *Can. Geotech. J.*, **42**(3), 752-762.

Burns, J.Q. and Richard, R.M. (1964), "Attenuation of stresses for buried cylinders", *Proceedings of Soil Symposium on Soil-Structure Interaction*, University of Arizona, Tucson, AZ, USA, pp. 379-392.

Cameron, D.A. (2005), "Analysis of buried flexible pipes in granular backfill subjected to construction traffic", Ph.D. Thesis, Graduate School of Engineering, University of Sydney, Sydney, Australia.

Cho, S. (2003), "Behaviour of Flexible Plastic Pipes with Flowable Backfill in Trench Conditions", Ph.D. Thesis, University of Houston, Houston , TX, USA.

Corey, R., Han, J., Khatri, D. and Parsons, R. (2014), "Laboratory study on geosynthtetic protection of guried steel-reinforcement HDPE pipes from static loading", *J. Geotech. Geoenviron. Eng.*, **140**(6), 04014019.

Hoeg, K. (1966), "Pressure distiribution on underground structural cylinders", Technical Report, No. AFWL TR 65-98, Kirtland Air Force Base, Albuquerque, NM, USA.

Hurd, J.O. (1986), "Field performance of corrugated polyethylene pipe culverts in Ohio", Serial of Transportation Research Record (TRR), Issue No. 1087, pp. 1.

Khatri, D.K., Han, J., Parsons, R.L., Young, B., Brennan, J.J. and Corey, R. (2013), "Laboratory evaluation of deformations of steel-reinforced high-density polyethylene pipes under static loads", *J. Mater. Civil Eng.*, **25**(12), 1964-1969.

Marston, A. and Anderson, A.O. (1913), Bulletin No. 31, Iowa Engineering Experiment Station, Ames, IA, USA.

Selig, E.T., DiFrancesco, L.C. and McGrath, T.J. (1993), "Laboratory tests of buried pipe in hoop Compression", *Buried Plastic Pipe Technology*, (ASTM STP 1222), PA, USA, pp. 119-132.

Spangler, M.G. and Shafer, G.E. (1941), "Structural design of flexible pipe culverts", Bulletin No 153, Iowa Engineering Experiment Station, Ames, IA, USA.

Sun, Z., Gong, X., Yu, J. and Zhang, J. (2013), "Analysis of the displacement of buried pipelines caused by adjacent surcharge loads", *International Conference on Pipelines and Trenchless Technology*, Xi'an, China, October.

Talesnick, M.L., Xia, H.W. and Moore, I.D. (2011), "Earth pressure measurements on buried HDPE pipe", *Geotechnique*, **61**(9), 721-732.

Terzi, N.U. (2007), "Investigation of the effects of vertical and lateral loads on the stability of buried pipes", Ph.D. Thesis, Institute of Natural and Applied Science, Yıldız Technical University, İstanbul, Turkey.

CC