

Experimental Investigation and Visualization of Failure Surfaces in Pipe-Soil Interaction Problems Using PIV Technique



Selçuk Bildik, Peter Rogenbuke, Gizil Tak, Baran Tulan,
and Özer Çinicioğlu

Abstract In this study, the effect of relative density on bearing capacity was investigated for cases in which a pipe is buried within the zone of influence. As a novelty, failure mechanisms are experimentally determined using Particle Image Velocimetry (PIV). Within the scope of the study, six different physical model experiments were carried out for this purpose. In these experiments, the load imposed on the neighboring surficial foundation model and the resulting displacements relationship were also determined. The results suggest density dependency of the distribution of deformations.

Keywords Relative density · PIV method · Pipe-soil interaction · Bearing capacity · Failure surface

1 Introduction

Infrastructures such as buried pipeline systems have great importance in daily life. Sewer systems enable people to process the municipal waste, and oil pipelines contribute to transporting petroleum products.

S. Bildik (✉) · G. Tak
Department of Civil Engineering, Nisantasi University, İstanbul, Turkey
e-mail: selcuk.bildik@nisantasi.edu.tr

G. Tak
e-mail: giziktak@gmail.com

P. Rogenbuke · B. Tulan · Ö. Çinicioğlu
Department of Civil Engineering, Bogazici University, İstanbul, Turkey
e-mail: peterogenbuke@gmail.com

B. Tulan
e-mail: baran.tulan@boun.edu.tr

Ö. Çinicioğlu
e-mail: ozercinicioğlu@boun.edu.tr

One of the most common materials used for such systems is PVC pipes. The most important reasons are that they are cheaper and non-corrosive, and due to that fact, they are less susceptible to microbiological growth. Furthermore, their durability is competitive with other materials such as steel.

The analysis and design of such systems require the consideration of soil-structure interaction [1]. When designing buried pipeline systems, estimating parameters such as displacements, internal stresses caused by transported materials, and external stresses caused by the surrounding soil are necessary.

In the literature, many researchers conducted experiments to evaluate the performance of buried pipes, focusing on the load–displacement behavior of pipes [2–7]. Additionally, there is limited research about pipe-soil interaction in terms of bearing capacity [6, 8, 9].

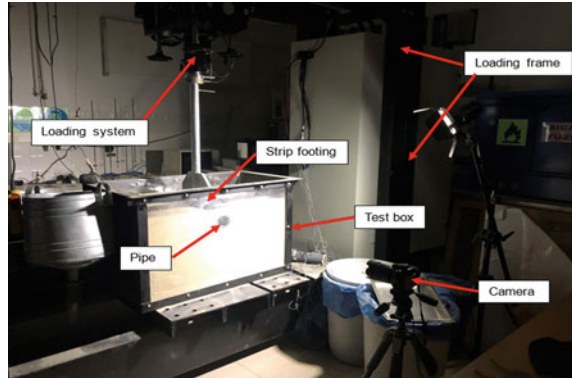
One of the most popular techniques for image analysis, called Particle Image Velocimetry (PIV), was used for the analyses of the images captured during the model tests conducted in this study. PIV is a non-invasive velocity measuring procedure that adapts to geotechnical applications [10]. In this study, MATLAB based GeoPIV_RG software [11] was used. The software operates by dividing a reference image into user-defined meshes and calculates displacements between consecutive images regarding the reference image. This way, displacement vector field can be determined. With the GeoPIV_RG algorithm, the formation of the failure surface in the soil can be observed with a map consisting of different colors indicating different displacement surfaces. The obtained results are presented and discussed.

2 Experimental Studies

2.1 Experimental Setup

Physical model tests were carried out in a rigid box that contains backfill of target density with a pipe buried. Pipe location was varied between experiments. In the tests, a model surficial continuous footing was loaded to observe backfill-pipe-foundation interaction. The model tests were designed to examine the effect of pipe embedment depth. The tests were recorded by employing different types of data recorders which can measure both load acting on the foundation model and the resulting displacements. The steel frame in which the model tests are conducted allows the preparation of a model backfill with dimensions 100 cm × 50 cm × 60 cm. The front and back sides of the frame are made of plexiglass for capturing consecutive images of soil deformations. For this purpose a Nikon D90 camera was used and the images are later analyzed using GeoPIV-RG. In the model tests, a strip foundation model is placed with dimensions of 50 cm × 10 cm × 3 cm on the backfill and loaded using a loading piston. Foundation loads and the resulting displacements were measured using a load cell and LVDT transducers, respectively. Furthermore, pipe strains were measured using TML brand strain gauges. All measurements are and recorded via

Fig. 1 Overview of the test setup



National Instruments (NI) modules equipped with NI developed LabView software. Three different load cells having different capacities of 500 kg, 1 tonne, and 2 tonnes were used throughout the experiments. LVDT stroke length is 150 mm, and the strain gauges are GFLA-6-50-4L type. Strain gauges were attached to the PVC pipe with a unique cyanoacrylate adhesive. Experimental setup is shown in Fig. 1.

The rate of the loading piston was kept constant at 10 mm/min. The images were captured with a rate of one photo for every 12 s. This corresponds to 2 mm of piston displacement per image making it easier to translate pixel-based displacements to actual displacements. After the completion of the tests, captured images were analyzed using GeoPIV_RG using the initial image as the reference which is meshed with 50px × 50px-sized patches (Fig. 2). The results were expressed in millimeters. As a result, the stress–displacement curves were presented are plotted with 2 mm intervals up to 10 mm displacement, which corresponds to the 10% of the foundation width, due to adopted failure criterion [12].

Fig. 2 PIV analysis area and mesh

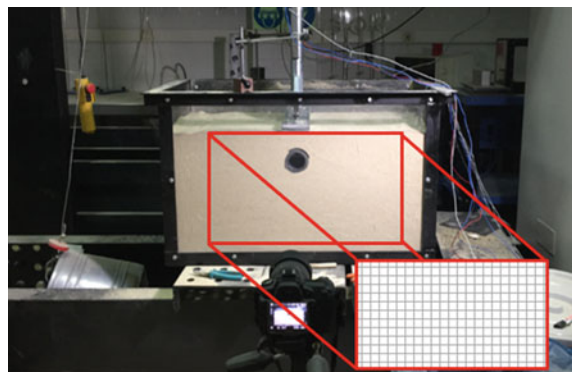
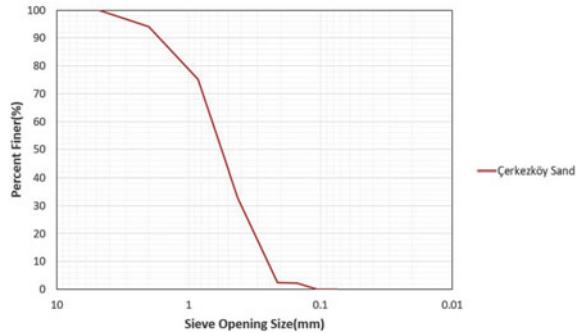


Table 1 Index properties of Çerkezköy sand

Soil property	Value
Classification	SP
Median particle size (D_{50})	0.64
Coefficient of uniformity (C_u)	2.37
Coefficient of curvature (C_c)	0.93
Specific gravity (G_s)	2.62
Maximum void ratio (e_{max})	0.83
Minimum void ratio (e_{min})	0.50
Average sphericity (S_{ave})	0.560
Average roundness (R_{ave})	0.749

Fig. 3 Grain size distribution of Çerkezköy sand



2.2 Soil Properties

For this research, sand obtained from Çerkezköy region of İstanbul was used. Index properties of Çerkezköy Sand are summarized in Table 1 and (Fig. 3).

2.3 Experimental Method

In the scope of this experimental study, 6 model tests were conducted, in which them of them were with the pipe being buried at an embedment ratio of $H/D = 1$ and the other three were without the buried pipe. Each case was examined for different relative densities (D_r) of 35, 50 and 65%. The configuration of the tests are illustrated in Fig. 4 where H is the vertical distance between the bottom of the foundation and the crest of the pipe and D is the pipe diameter which is constant as 75 mm. The required relative density of the sand soil was established by calculating the total soil mass necessary for the whole volume of the frame, then placing and compacting it in ten layers, each layer corresponding to 1/10 of the volume of the frame hence 1/10 of the required soil mass. Details of the model tests conducted are given in Table 2.

Fig. 4 Pipe embedment

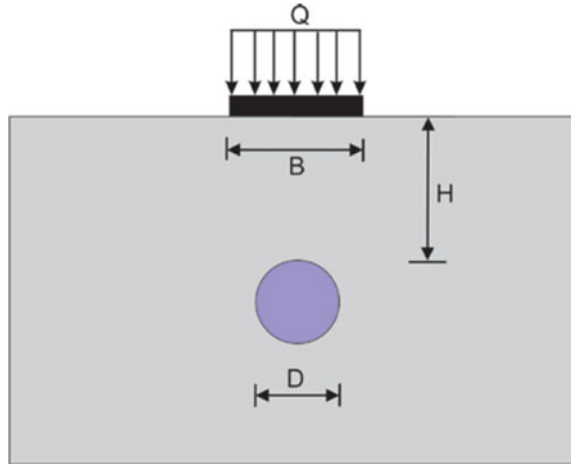


Table 2 Test program

Test no	Relative density of sand (D_r)(%)	Embedment ratio of pipe (H/D)
1	35	–
2	35	1
3	50	–
4	50	1
5	65	–
6	65	1

3 Results and Discussion

This study aims to examine the effect of the buried pipe and different sand relative densities on the bearing capacity of neighboring surficial strip foundations. Figure 5 shows the experimental distribution of vectorial displacements and resultant displacement contours obtained from GeoPIV_RG analyses for 10 mm foundation settlement, which corresponds to 10% of the foundation width that is considered to correspond to failure in this study. It is clear from the analysis results that pipe affects the wedge size and stress distribution due to creating a non-continuous soil zone. Also, resultant contours indicate that displacement zones created just below the pipes and the lowest relative density Çerkezköy sand have the largest displacement zone just below the pipe, as expected.

Figure shows the stress-displacement behavior at 10 mm displacement, which corresponds to 10% of the foundation width of the Çerkezköy Sand with and without the presence of the pipe. As expected, for the case without pipe, the highest load is carried when the relative density is the highest. For the case with pipe, the loading

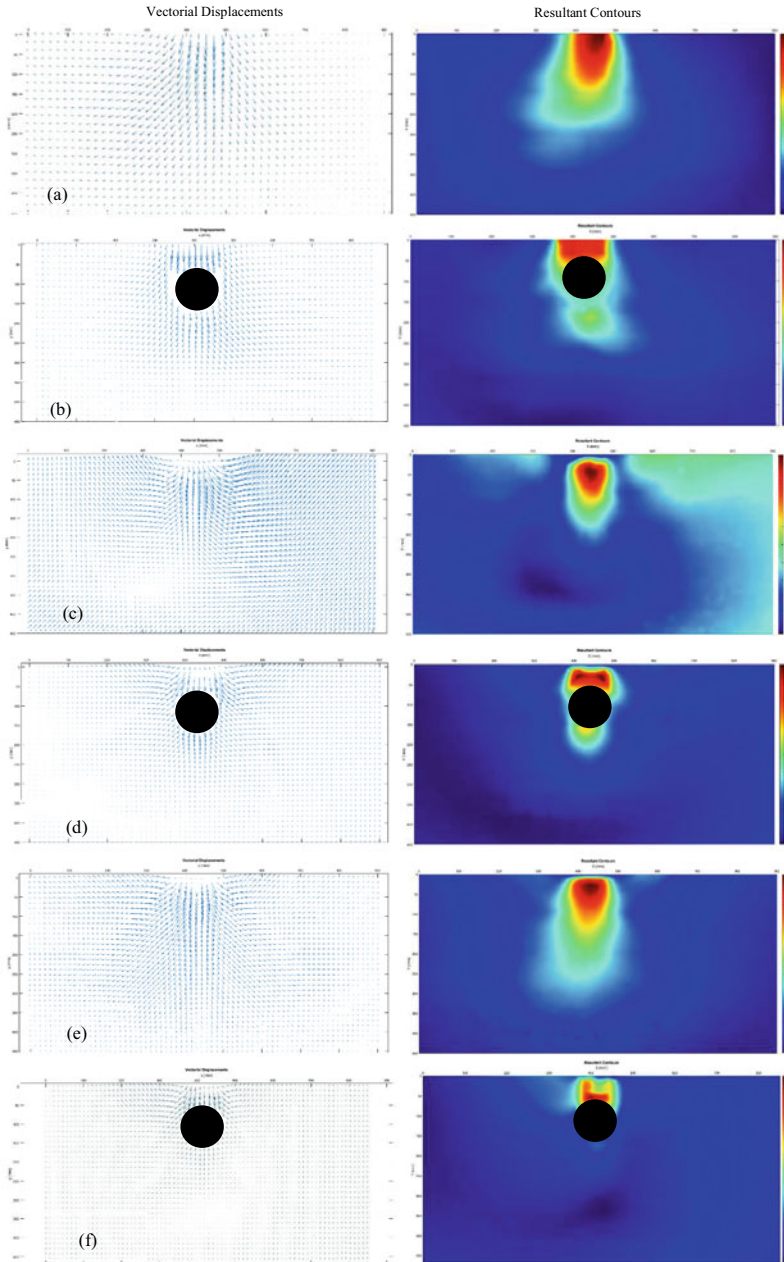


Fig. 5 Vectorial displacements and resultant displacement contours from GeoPIV_RG. **a** Dr: 35% without pipe, **b** Dr: 35% H/D: 1, **c** Dr: 50% without pipe, **d** Dr: 50% H/D: 1, **e** Dr: 65% without pipe, **f** Dr: 65% H/D: 1

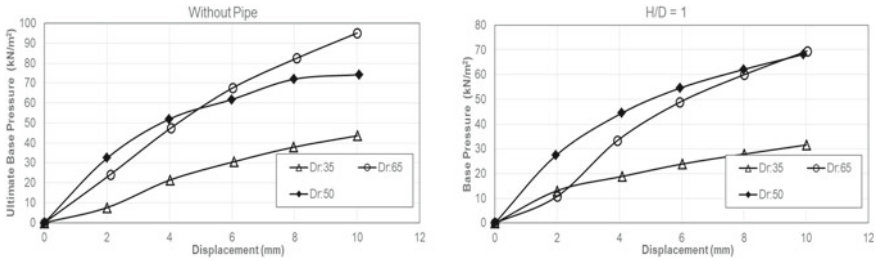


Fig. 6 Stress- displacement behavior of Çerzekköy sand with and without pipe

capacity of the soil at 35 and 65% relative densities drops around 70%, whereas 50% relative density drops around 90% of the case without pipe load values (Fig. 6).

4 Conclusions

In this study, six physical model tests and GeoPIV_RG analyses were conducted to observe the effects of the presence of the pipe and relative density on the deformation of the soil-pipe-foundation system under loading. Pressures and displacement acting on the model foundation were measured, and deformation of the soil strata was visualized by using GeoPIV_RG analyses. GeoPIV_RG analysis accurately envisioned the deformation zones of different sand relative densities. It is understood from the correct separation of the sizes and geometries of the displacement fields obtained from three different analysis results from each other. Furthermore, PIV_analyses were also accurate in visualizing the deformation zones with pipe since it can be seen that from the results, pipe leads to separate deformation fields in sands of different relative densities as expected.

Further studies could be carried out to investigate the effect of geosynthetic on deformation fields and bearing capacity of soil-pipe-foundation system under loading by using GeoPIV_RG analyses. Moreover, further research could examine different soil types using strain contours which can be provided by GeoPIV_RG analyses.

Acknowledgements The work presented in this paper was carried out with funding from TUBITAK (The Scientific and Technological Research Council of Turkey) grant number 116R020.

References

1. Richard A (1973) Parmelee Investigation of soil-structure interaction of buried concrete pipe. Highway Res Board 443:32–39
2. Selig ET, DiFrancesco LC, McGrath TJ (1993) Laboratory tests of buried pipe in hoop Compression, Buried Plastic Pipe Technology, (ASTM STP 1222). PA, USA, pp 119–132

3. Brachman RWI (1999) Structural performance of Leachete collection pipes. PhD thesis, Department of Civil and Environmental Engineering, University of Western Ontario, London, ON, Canada
4. Cho S: Behaviour of flexible plastic pipes with flowable backfill in trench conditions. PhD thesis, University of Houston, Houston, TX, USA
5. Cameron DA (2005) Analysis of buried flexible pipes in granular backfill subjected to construction traffic. PhD thesis, Graduate School of Engineering, University of Sydney, Sydney, Australia
6. Terzi NU (2007) Investigation of the effects of vertical and lateral loads on the stability of buried pipes. PhD thesis, Institute of Natural and Applied Science, Yıldız Technical University, İstanbul, Turkey
7. Talesnick ML, Xia HW, Moore ID (2011) Earth pressure measurements on buried HDPE pipe. *Geotechnique* 61(9):721–732
8. Brachman RWI, Krushelnitzky RP (2005) Response of a landfill drainage pipe buried in a trench. *Can Geotech J* 42(3):752–762
9. Bildik S (2013) Investigation of buried pipe systems in different soil and loading conditions. PhD thesis, Institute of Natural and Applied Science, Cukurova University, Adana, Turkey
10. Lesniewska D, Wood DM (2011) Granular materials at meso and macro Scale: photo-elasticity and digital image correlation. In: *Advances in bifurcation and degradation in geomaterials*, Springer Series in Geomechanics and Geoengineering, vol 11
11. Stanier SA, Blaber J, Take WA, White DJ (2015) Improved image-based deformation measurement for geotechnical applications. *Can Geotech J* 53(5):727–739
12. Vesić A (1975) Bearing capacity of shallow foundations. In: Winterkorn, HF, Fang HY (eds) *Foundation engineering handbook*. Van Nostrand Reinhold, New York, pp121–147