ICONHIC2019
2nd International Conference on Natural Hazards & Infrastructure
23-26 June, 2019, Chania, Greece

Experimental investigation on soil-pipe interaction under cyclic lateral loading

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1 INTRODUCTION & SCOPE OF WORK

Natural gas pipelines are one of the most essential civil infrastructures in many developed countries. Failure of natural gas pipelines may lead to severe disruption of the functionality of an urban society. A large portion of the natural gas pipelines is embedded in soil to protect them from potential damage. In the event of an earthquake, the embedded natural gas pipelines are expected to deform with soil. Due to the differences in the stiffness and mass of the natural gas pipeline in comparison with those of the soil replaced by the pipeline, there is non-negligible interaction between the natural gas pipeline and the surrounding soil.

The interaction between natural gas pipeline and surrounding soil can be numerically simulated with finite element modelling (FEM) approach as shown in (Psyrras et al. 2019) or using a computationally efficient Winkler springs. The former provides more realistic response than the latter, but it requires significant computing time if nonlinearity of soil and contact between soil and pipe need to be modelled. Thus, it is not feasible to apply the method for a regional seismic loss assessment of natural gas pipelines. The Winkler spring approach is computationally very efficient. Yet, the method requires calibration of spring properties against experimental results. There exists a modelling guideline based on very simple bi-linear springs (ALA 2001). Such springs, however, do not consider coupled responses of lateral- and vertical-resistance of near field soil. There were large scale experiments where soil-pipe interaction was investigated (O'Rourke et al. 2008; Paulin et al. 2018; Sarvanis et al. 2018 among many others) but the experiments with multi-axial control and with cyclic loads are scarce.

The long-term objective of the research project is to develop a computationally efficient macro element that can simulate soil-pipe interaction considering the coupled behaviour of lateral- and vertical responses. As a first step of the project, the authors carried out laboratory experiments to understand cyclic behaviour of soil-pipe interaction when the soil and pipe develops relative deformation. This extended abstract presents the experimental study and preliminary findings from experiments.

2 METHODOLOGY

An experimental apparatus is designed to understand cyclic soil-pipe interaction considering several parameters that may influence the interaction such as embedment depth, density of soil, dimension of pipe, loading direction, etc. The experimental apparatus, shown in Figure 1, mainly consists of a soil box with dimension of 1.2 m in depth, 1.7 m in length, and 0.2 m in thickness, pipe with a shaft illustrated in Figure 1

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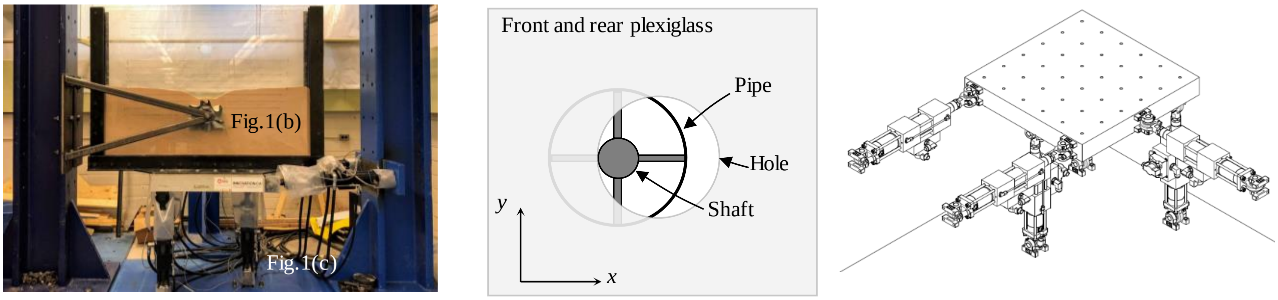
(b), and multi-axial control system in Figure 1 (c). The thickness of the soil box can be reduced to 0.15 m to investigate boundary effects (e.g. friction between soil and plexiglass, or resistance of soil that may stuck between the plexiglass panels and pipe ends). The shaft that is fixed with the pipe goes through holes in the front and rear plexiglass panels. The shaft is fixed to the left reaction column. To prevent leakage of soil through the gap between the pipe ends and the holes (shown in Figure 1 (b)), a flexible membrane is attached between the pipe ends and the plexiglass panels. To impose relative deformation between the pipe and the soil, the soil box is fixed to a multi-axial hydraulic control system shown in Figure 1 (c). The hydraulic actuators include load cell such that multi-axial components of resisting forces resulting from soil-pipe interaction can be recorded. The hydraulic actuators are reacted to the column at the right. The experimental setup can impose any combination of horizontal and/or vertical relative deformation between the pipe and the soil.



(a) Overview of experimental setup (box dimension: 1.2 m × 1.7 m × 0.2 m)

(b) Mechanism to impose relative deformation between soil and pipe

(c) Six-DOF hydraulic control system to impose multi-axial deformation and to read reaction force

Figure 1. *Configuration of experimental apparatus*

The dimension of the experimental setup is determined considering the displacement and force capacity of the hydraulic actuators, as well as the available space in the testing facility. Mathematical derivation of a similitude law confirmed that the small-scale test results with 1g gravitational field can be scaled to obtain expected responses of full-scale soil-pipe interaction. Before the construction of the plexiglass, detailed finite element analyses are also carried out with a range of soil parameters to numerically verify the similitude law as well as to confirm that the actuator capacity exceeds the required force demand.

The hydraulic actuators are dynamic actuators which is beneficial in controlling relative density of the soil. To achieve loose sand with small relative density, the soil is spread through a conduit without densification. Based on the volume and weight of soil used for the soil preparation, the relative density of loose sand in the soil box was found to be 23%. To achieve dense sand, after uniformly depositing soil with thickness of 5 cm, vertical vibration of 25Hz with amplitude of 0.5 mm is imposed for 30 sec. This densification method resulted in relative density of 92% and could achieve repeatable test results.

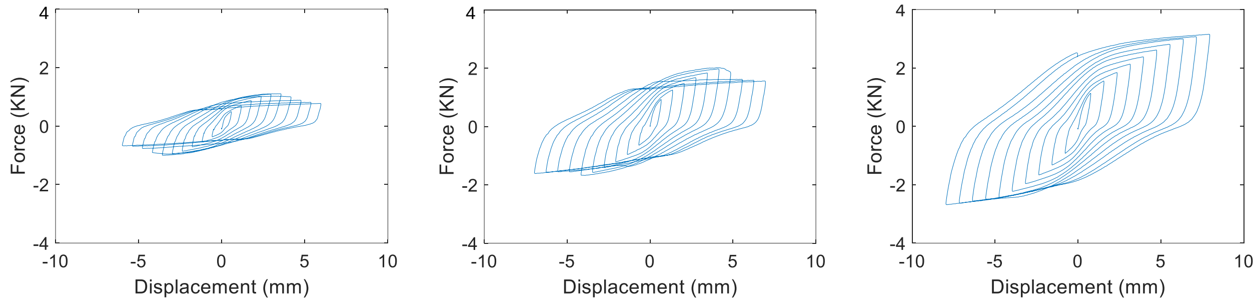
The soil used for the experiment is Lake Sand (LS-80), which is poorly graded fine sand with grain size between 0.15 to 0.21 mm. Before running the soil-pipe interaction tests, several standard tests were carried out to identify properties of the soil such as grain size distribution, specific gravity ($G_{s,20^\circ} = 2.60$), minimum dry weight ($\gamma_{d,min} = 13.89\ KN/m^3$), maximum dry weight ($\gamma_{max} = 16.55\ KN/m^3$), and peak and residual friction angle as a function of relative density.

In total, 20 experiments were conducted with dense sand. Two pipe dimensions (100 mm and 50 mm diameter) were tested under monotonic and cyclic loading in the horizontal direction. The 100 mm pipe was tested in dimensionless burial depths ranging from 1.5 to 3.5. The 50 mm pipe was tested in depths ranging from 2.0 to 6.0. Each test was repeated to verify the consistency of the results. The results appear to be consistent to a satisfactory degree. Both pipes were tested in loose sand with relative density of 23%. The prototype was tested in a range of dimensionless burial depths 1.5 to 3.0.

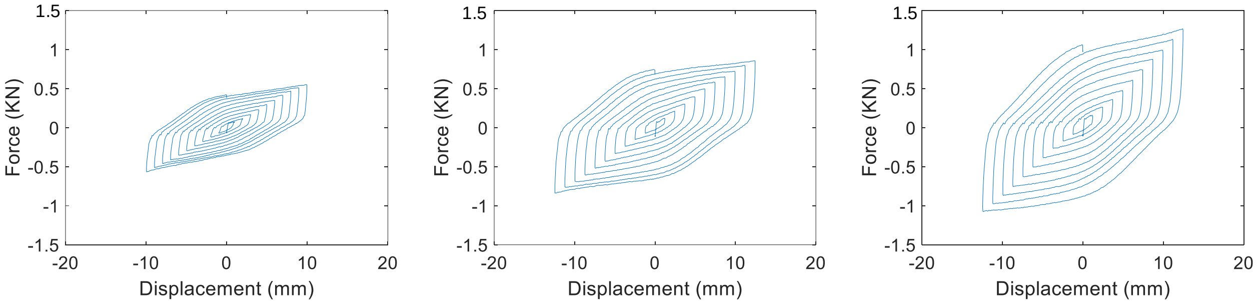
3 RESEARCH OUTCOMES

Sample test results are summarized in Figure 2 from experiments with pipe diameter of 100 mm and soil thickness of 200 mm. Due to the weight of the soil and the specimen mount platen, the vertical actuators develop frictional resistance. Thus, at the end of each experiment, the pipe was detached from the braces and the test was run again with exactly the same loading protocol to identify frictional resistance. The results shown in Figure 2 is after removing frictional resistance. Figures 2 (a) through 2 (c) are from dense soil with normalized depth of 1 to 3, respectively. It can be observed that for shallow burial depth (Figure 1 (a) and 1(b)), the soil develop peak resistance, which eventual deteriorate as the displacement increases. The deterioration of the strength is due to loosening of soil around the surface as the displacement demand increases. When the burial depth is deep enough (Figure 1(c)), the strength of the soil continue to increase, which is primarily because the soil was not fully densified, and the distance from the pipe to the soil surface is far enough not to disturb soil around the surface. It can be also observed that as the embedment depth increase, the resistance of soil increases. In addition, the force deformation relationship is hard to be represented with simple bi-linear relationship which is widely used in soil-pipe interaction analysis.

Figures 2(d) through 2(f) shows the test results from loose soil with normalized burial depth from 1 to 3. In loose soil, all test results show isotropic hardening behaviour because each cycle of deformation demand density soil adjacent to the pipe even for the shallow burial depth case.



(a) Dense, h/d = 1 (b) Dense, h/d = 2 (c) Dense, h/d = 3



(d) Loose, h/d = 1 (e) Loose, h/d = 2 (f) Loose, h/d = 3

Figure 2. *Example test results of pipe with diameter of 100 mm and soil thickness of 200 mm*

The test results are being further analyzed to understand interaction between horizontal and vertical responses, and to develop a macro element which can capture multi-axial nonlinear behaviour of soil-pipe interaction. Overall test results will be presented in future publications.

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