STUDY ON SOIL-PIPELINE INTERACTION DUE TO LARGE GROUND DEFORMATION

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ABSTRACT :
Earthquake-induced Permanent Ground Deformation (PGD) occurring as a fault deformation and landslides can significantly affect underground lifelines such as buried gas pipelines. To assess the integrity of the pipelines against such ground deformation, it is important to quantitatively evaluate the interaction between the pipelines and the surrounding soils.

The soil pipelines interaction specified in the major seismic design guidelines for buried pipelines has s bilinear force-displacement relationship curve. The actual experimental results, in case of the dense backfill conditions, conducted by Trautmann and O'Rourke, however, showed that the force decreased gradually after the relative displacement between soil and pipe reached to such a degree that the maximum was observed. In the case of PGD, therefore, it is expected that the soil-pipeline interaction is much smaller when the large ground deformation occurs due to the collapse of the soil.

In this study, full-scale experiments were conducted to investigate into the effect of the decrease in soil-pipeline interaction. The 100-mm-diameter pipe was installed and backfills in a test compartment. The test pipe was installed at a 0.6m depth from the ground surface in the dense backfill conditions. The soil-pipeline interaction in the lateral direction was measured up to about 150mm relative displacement between soil and test pipe.

Furthermore, distinct element analyses were conducted to investigate the deformation behavior of test pipe and the surrounding soils.

KEYWORDS:
Soil-Pipeline Interaction, Permanent Ground Deformation, Distinct Element Method

1. Introduction

Earthquake-induced Permanent Ground Deformation (PGD) which occurs as surface faults, liquefaction-induced soil movements, and landslides, can cause damage to underground lifelines such as buried pipelines. It was reported that buried pipelines such as gas and water pipelines were damaged by PGD in the 1906 San Francisco, the 1964 Niigata, the 1971 San Fernando, the 1979 Imperial Valley, the 1983 Nihonkai-chubu, the 1989 Loma Prieta, the 1994 Northridge and the 1995 Hyogoken-nanbu earthquakes. More recent earthquakes have provided additional evidence for the important of liquefaction, faults rupture and landslides through their effects on a variety of electrical, gas and water supply lifelines.

To assess the integrity of the pipelines against such ground movements, it is important to quantitatively evaluate the interaction between the pipelines and the surrounding soils. The soil-pipeline interaction specified in the major seismic design guidelines for pipelines has a bilinear force-displacement relationship curve. The actual experimental results conducted by Trautmann and O'Rourke, however, showed that the force gradually degreased when the relative displacement between the soil and pipes in the lateral direction is 0.1m in the case of dense sand for backfill. In case of PGD, therefore, it is expected that the soil-pipeline interaction is much smaller when the ground displacement is a few meters due to collapse of the soil.

In this study, full-scale experiments were conducted to investigate into the effect of the decrease in soil-pipeline interaction. The 100-mm-diameter pipe was installed and backfills in a test compartment. The test pipe was installed at a 0.6m depth from the ground surface in the dense backfill conditions. The soil-pipeline interaction in the lateral direction was measured up to about 120mm relative displacement between soil and test pipe. Furthermore, distinct element analyses were conducted to investigate the deformation behavior of the surrounding soils.

Part of this work has been already presented in International Conference on Computational and Experimental Engineering and Science.

2. Experimental studies

2.1. Experimental Procedures

Full-scale experiments were conducted to investigate into the effect of the decrease in soil-pipeline interaction. A test pipe that was 100mm in diameter was installed and backfilled in the test compartment which had inside dimensions of 3.0m by 2.0m by 2.0m deep and was on the shaking table. The test pipe was installed at a 0.6m depth from the ground surface and pulled by hydraulic jacks through two steel wires. Figure 1 shows a top and plain view of the experimental setup. Acrylic boards were placed around the side wall of the test compartment to reduce the friction between the soil and side walls of the test compartment. The test pipe was weighted so that the test pipe was filled up with concrete not to be deformed during the experiments. Counter weight systems canceled out the extra weight of the test pipe. The gap, which was kept in the test compartment to cater for the test pipe displacement, was covered using a rubber sheet in both sides.

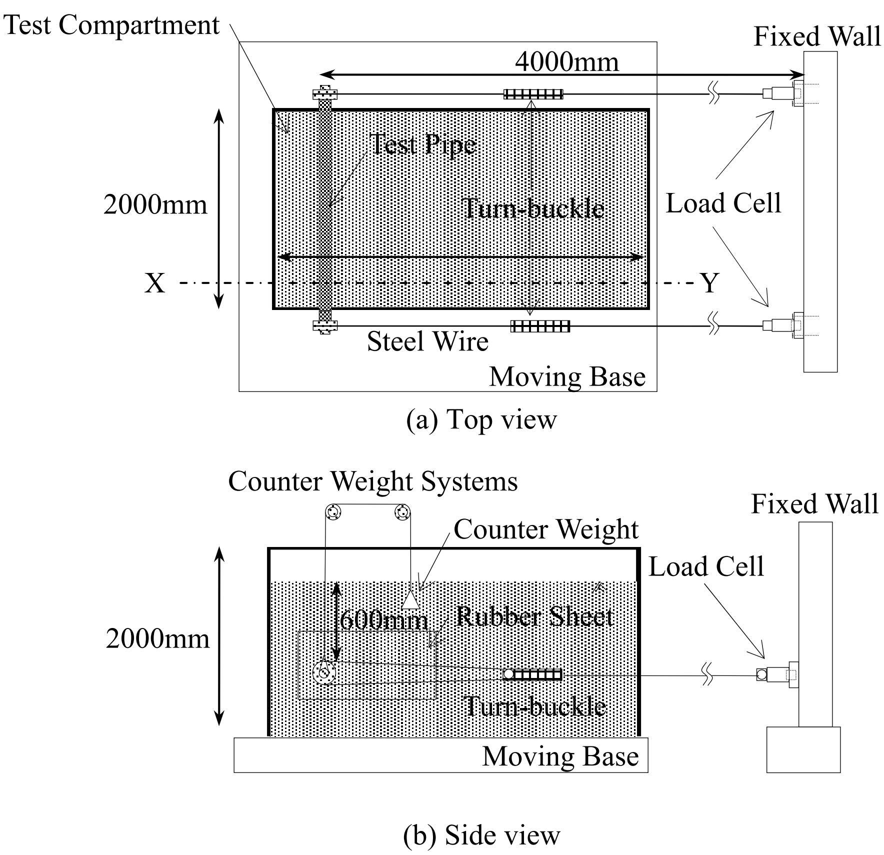


Figure 1 Experimental setup

Two kinds of test, Test 1 and Test 2 were conducted. Test 1 was performed with loose backfill conditions. The sand used for backfill is called "Chiba Sand", which was clean sand. The properties are summarized in Table 2.1 and satisfy the standard for backfill sand specified by the Bureau of Construction of the Tokyo Metropolitan Government. The grain size curve for the sand is shown in Figure 2. The sand was placed and not compacted with strict control of in situ density. Test 2 was performed with dense backfill conditions. The sand was placed and compacted in 0.15m lifts with strict control of in situ density.

Table 2.2 summarizes the experimental conditions of the sand before the tests. In this table, internal friction angles obtained from tri-axial compression test with a strain rate of 1%/min. were determined based on the dry unit weight using the relationship shown in Figure 3.

Table 2.1 Physical properties of Chiba Sand

Specific gravity (Mg/m^3)	2.7	
Grain size distribution	Gravel (%)	0.0
	Sand (%)	97
	Silt (%)	3.4
Maximum dry unit weight (kN/m^3)	17	
Optimum water content (%)	17	

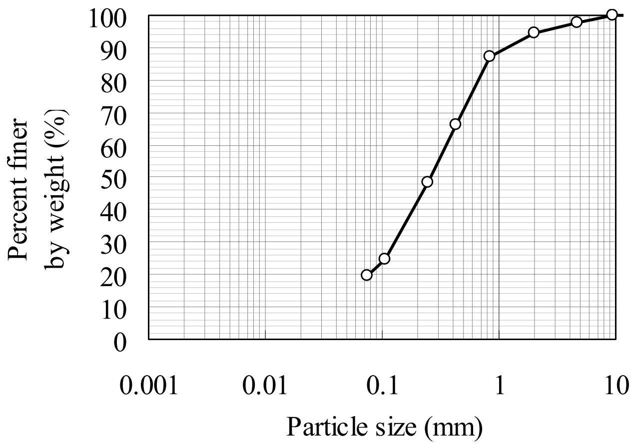


Figure 2 Grain size distribution

Table 2.2 Experimental conditions

Test Number	Test 1	Test 2
Backfill conditions	loose	dense
Water content (%)	0.00	
Dry unit Weight ($kN/^3$)	14.9	16.2
Internal friction angle (degree)	35.2	42.0

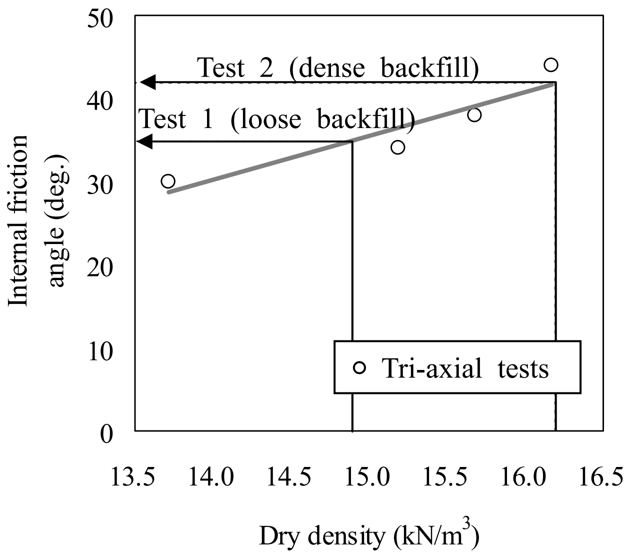


Figure 3 Relationship between dry weight and internal friction angle

During the experiments, the test pipe was pulled for 0.15m in the lateral direction. The rate of displacement of hydraulic jacks was approximately 10mm/sec. As shown in Figure 1, the reaction force was measured with two load cells connected to the steel wires installed between the test pipe and fixed wall.

2.2. Experimental Results

Figure 4 shows the plane view of soil slip observed at Section X-Y, which is shown Figure 1 when the about half of sand in a soil box was removed after Test 2 (dense backfill conditions). In Figure 4, the slip line reached the ground surface at an angle of 43 degrees to horizontal direction. And the width of the heaving zone was approximately 800mm. In case of Test 1 (loose backfill conditions), the obvious deformation behavior of the surrounding soils was not observed.

Figure 5 shows the experimental results: the force per unit projected area versus relative displacement of the test pipe in the ground. In case of Test 2 (dense backfill conditions), the force gradually decreased after the relative displacement between soil and test pipe reached to such a degree that maximum force was observed. In case of Test 1 (loose backfill conditions), the force was a steady state with increasing displacement.

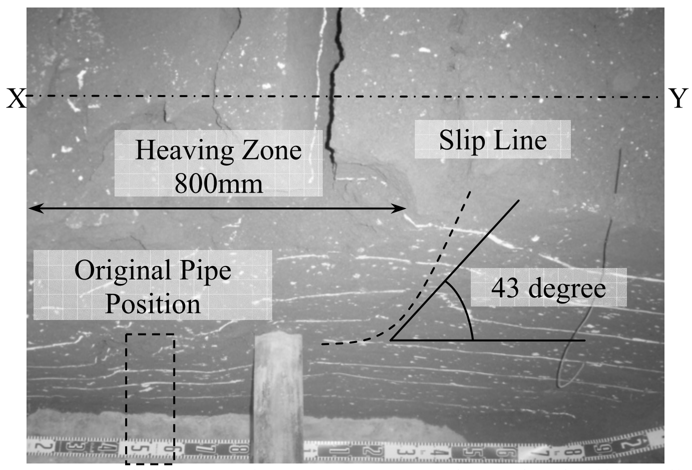


Figure 4 Ground deformation after Test 2 (dense backfill conditions)

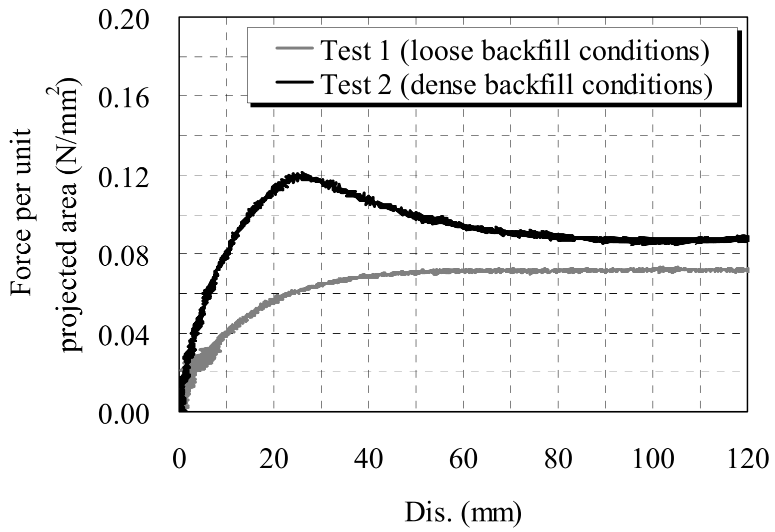


Figure 5 Experimental results

3. Analytical studies

3.1. Analytical model

2-Dimensional numerical studies were conducted to simulate the previous experiments by means of the Distinct Element Method (DEM). PFC-2D version 3.10 was used as a solver. The sand is represented by an assembly of disks with diameter equal to 10mm. Figure 6 shows the numerical model. The numerical particles are 7,958. In case of simulation of Test 2 (dense backfill conditions), the sand is represented by an assembly of bonding particles, which is composed of two disks in order to represent the friction force caused by the distorted shapes of sands. The size of numerical model is equal to that of the experimental one.

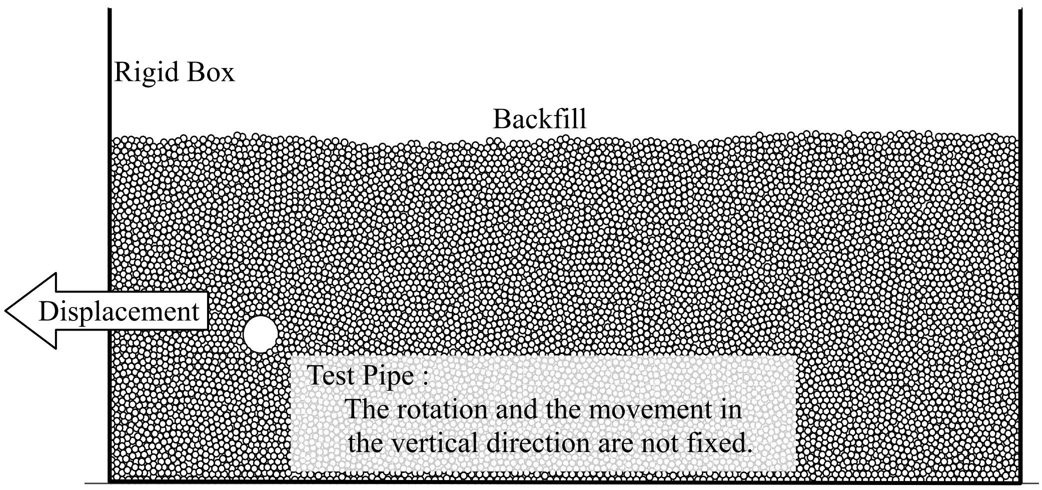


Figure 6 Analytical model

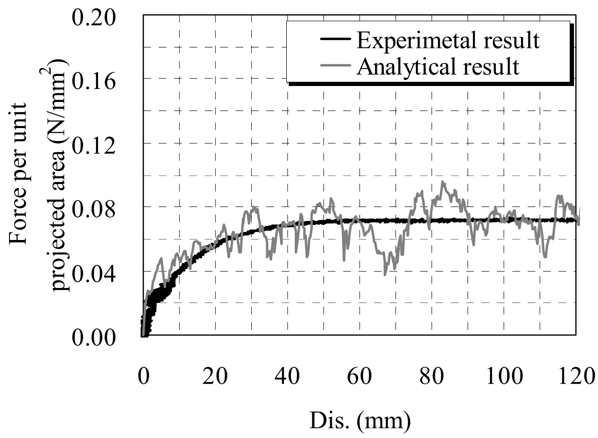
Numerical parameters were designed with the aim of introducing a numerical substitute for experimental conditions. Normal contact stiffness, share contact stiffness and friction coefficient was identified by conducting numerical tri-axial tests to reproduce the experimentally behavior as shown in Table 3.1.

Table 3.1 Identified Parameters

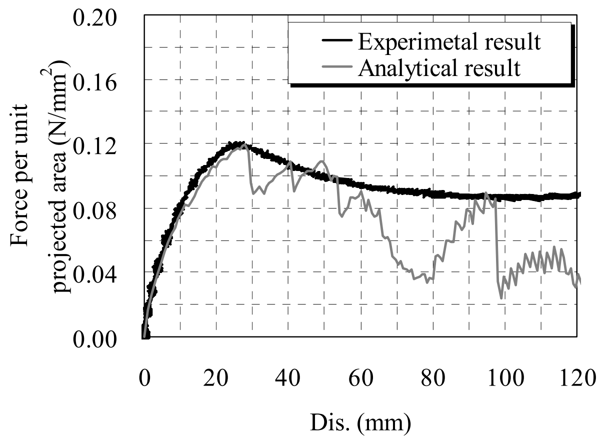
Test Number	Test 1	Test 2
Backfill conditions	loose	dense
Particle types	unit disk	bonding disk
Normal contact stiffness (MN/m)	40	20
Share contact stiffness (MN/m)	40	20
friction coefficient	0.18	0.80

3.2. Analytical results

Figure 7 shows the comparison between the analytical results and the experimental results in the form of the force per unit projected area and displacement curve. In case of Test 1 (loose backfill conditions), the analytical result agreed reasonably well with the experimental result for the maximum force and force-displacement curve. In case of Test 2 (dense backfill conditions), the analytical result agreed with the experimental result for the maximum force and force-displacement curve when the displacement was less than 50mm. The analytical result became unstable when the displacement was more than 50mm. In future works, the modeling of re-contact of bonded disks will be improved.



(a) Test 1 (loose backfill condition)



(b) Test 2 (dense backfill condition)

Figure 7 Analytical results

Figure 8 shows the displacements of particles when the peak value of the force was observed in case of Test 2 (dense backfill conditions). The area of the poor particles density was observed as shown in doted circle. This area agreed with the position where the slip line was observed after Test 2 (dense backfill conditions). It was considered that the appearance of the slip line had close relationship with the gradually decrease of the force.

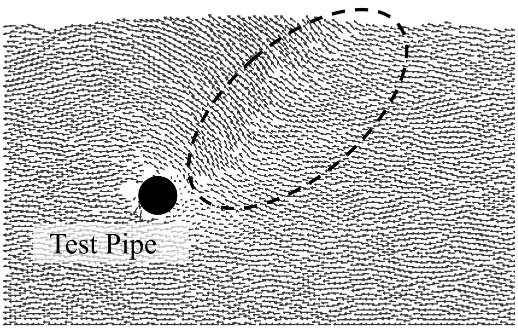


Figure 8 Displacements of particles

Conclusion

This paper investigated the decrease in soil-pipeline interaction by conducting full-scale experiments. In case of dense backfill conditions, the force decreased gradually after the relative displacement between soil and pipe reached to such a degree that the maximum force was observed. On the other hand, the decrease in the force was not observed in case of loose sand backfill.

Furthermore, Distinct Element Analyses were conducted to investigate the deformation behavior of test pipe and the surrounding soils. The analytical result agreed reasonably well with the experimental result for the maximum force and force-displacement curve. It was considered that the appearance of the slip line had close relationship with the gradually decrease of the force.

REFERENCES

O'Rourke, T. D. and Lane, P.A. (1989) . Liquefaction Hazards and Their Effects on Buried Pipelines. Technical Report, NCEER-89-0007, NCEER, Buffalo, NY.

Hamada, M. (1992). Large Ground Deformations and Their Effects on Lifeline: 1989 Nihonkai-Chubu Earthquake. *Proceedings of Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes Volume 1 Japanese Case Studies*.

O'Rourke, T. D. and Palmer, M. C. (1996). Earthquake Performance of Gas Transmission Pipelines. *Earthquake Spectra*, **20:3**, 493-527.

Oka, S. (1996). Damage of Gas Facilities by Great Hanshin Earthquake and Restoration Process. *Proceedings of 6th Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction*, 111-124.

Trautmann, C.H. and O'Rourke, T.D. (1985). Lateral Force-Displacement Response of Buried Pipes. *Journal of Geotechnical Engineering*, **111:9**, 1077-1092.

Trautmann, C.H., O'Rourke T.D and Kulhawy F.H. (1985). Uplift Force-Displacement Response of Buried Pipes. *Journal of Geotechnical Engineering*, **111:9**, 1061-1076.

Bureau of Construction of Tokyo Metropolitan Government. (1999). Specification for Civil Material, Tokyo, Japan.

Yoshizaki, K., O'Rourke, T.D. and Hamada, M. (2002). Large Deformation Behavior of Buried Pipelines with Low-angle Elbows Subjected to Permanent Ground Deformation. *Journal of Structural Mechanics and Earthquake Engineering*, **675:55**, 41-52.

Japan Gas Association. (2000). Recommended Practice for Earthquake Resistant Design of High Pressure Gas Pipelines, Japan Gas Association, Tokyo, Japan.

Sakanoue, T. and Yoshizaki, K. (2003). Experimental Study on the Effect of Lightweight Backfill for Enhancement of Earthquake Resistance of Buried Pipelines. *Proceedings of 22ND International Conference on Offshore Mechanics and Arctic Engineering*.

Sakanoue, T. (2008). Study on Soil-Pipeline Interaction due to Large Ground Deformation. *Proceedings of International Conference on Computational and Experimental Engineering and Science.*

Calvetti, F. and di Prisco, C. and Nova, R. (2004). Experimental and Numerical Analysis of Soil-Pipe Interaction. *Journal of Geotechnical and Geoenvironmental Engineering*, **130:12**, 1292-1299.