RECENT DEVELOPMENTS IN EVALUATION OF SOIL-PIPELINE INTERACTION FOR SEISMIC DESIGN OF BURIED PIPELINES

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ABSTRACT

Sometimes, strong seismic motions and earthquake-induced permanent ground deformation (PGD) such as surface fault deformations, liquefaction-induced soil movements, and landslides, may significantly affect buried pipelines.

Tokyo Gas has conducted many studies related to the seismic design of buried pipelines. To assess the integrity of pipelines against such ground movements, it is important to quantitatively evaluate the deformation behavior of pipeline. The interaction between the pipeline and surrounding soil, which is called "soil-pipeline interaction", significantly affects the pipeline deformation, and hence the soil-pipeline interaction plays a large role in seismic design.

This paper describes recent developments conducted by Tokyo Gas in the evaluating soil-pipeline interaction. We developed an analytical method to evaluate the effect of properties of the soil surrounding pipeline on the soil-pipeline interaction. We then evaluated the effect of expanded poly-styrene (EPS) for backfill on a reduction in soil-pipeline interaction by conducting full-scale experiments.

1. INTRODUCTION

In Japan, large-scale earthquakes frequently occur. Tokyo Gas is working to ensure that our customers can always use gas conveniently and safely for 24 hours a day, 365 days a year. Therefore, earthquake and disaster countermeasures are very important.

In Japan, to prevent the earthquake-related damage of transmission pipelines,seismic design guidelines were established by the Japan Gas Association (JGA). The current guidelines were established in response to the 1995 Hyogoken-Nanbu earthquake. The 1995 Hyogoken-Nanbu earthquake was caused by the activity of an inland active fault close to the Hanshin district, a large urban area. The very strong seismic motions were observed near the fault. The subsequent permanent ground deformation (PGD) such as surface fault deformations, liquefaction-induced soil movements and landslides were observed. These ground movements significantly affected underground lifelines including gas distribution pipelines. In this light, JGA revised these seismic design guidelines by reflecting such strong motions and PGD [1][2]. After the revision of these guidelines, Tokyo Gas has strengthened gas supply facilities according to the revised seismic design guidelines so that they can withstand an earthquake with a magnitude similar to that of the 1995 Hyogoken-Nanbu earthquake. Though the seismic design guidelines were established, in order to achieve more effective measures, that is, “site-specific design and strategic maintenance”,advanced technologies for evaluation of earthquake-resistance of buried pipelines are required. Therefore, Tokyo Gas has been conducting many studies related to the seismic design of buried pipelines. We believe that the results obtained enable us to realize more reasonable design and maintenance of pipelines subjected to seismic motions or PGD.

Our studies include three essential technologies for evaluating earthquake resistance of buried pipelines shown in **Figure 1:**

(1) Prediction method for ground movement due to seismic motion and PGD

(2) Evaluation method for soil-pipeline interaction

(3) Evaluation method for pipeline deformation.

This paper describes the recent developments made by Tokyo Gas in the method for evaluating soil-pipeline interaction (2).

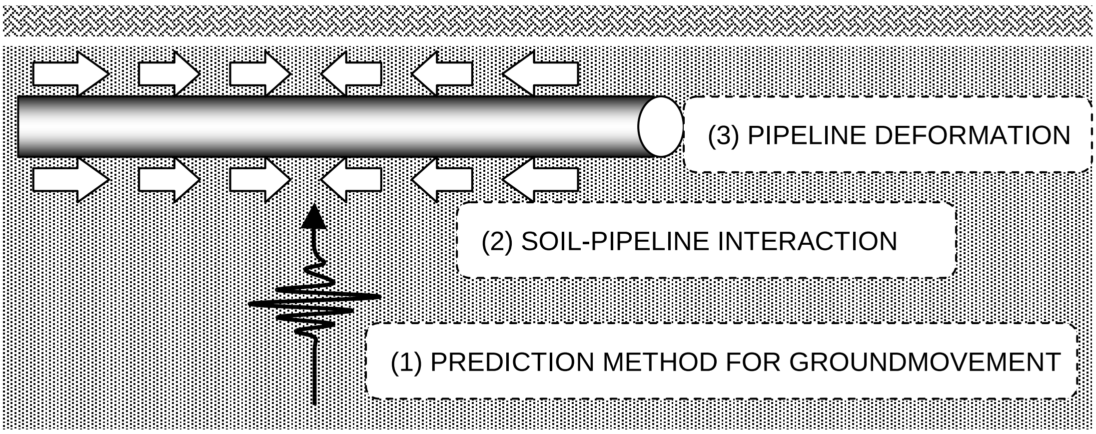


Figure 1: Three essential technologies for evaluating earthquake resistance of buried pipelines

2. SEISMIC DESIGN GUIDELINES AND SOIL-PIPELINE INTERACTION

The JGA revised the seismic design guidelines “Recommended Practice for Design of Gas Transmission Pipelines” in 2000 and established “Recommended Practice for Design of Gas Transmission Pipelines in Areas Subject to Liquefaction” in 2001 for the design of gas transmission pipelines subjected to PGD due to ground liquefaction during earthquakes. **Figure 2** shows the seismic design procedure for buried gas transmission pipelines subjected to liquefaction. As shown in **Figure2**, to evaluate the pipeline deformation against estimated ground displacement, the soil-pipeline interaction is required. The soil-pipeline interaction represents the external forces exerting the buried pipelines by the adjacent ground when the input due to PGD or seismic motions (**Figure3**) is provided. The soil-pipeline interaction is generally represented by

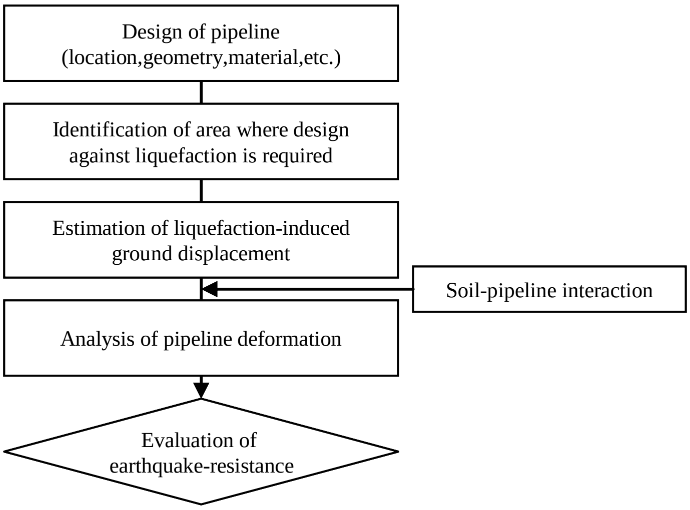


Figure 2: Procedure for evaluation of earthquake resistance of buried gas transmission pipelines subjected to liquefaction

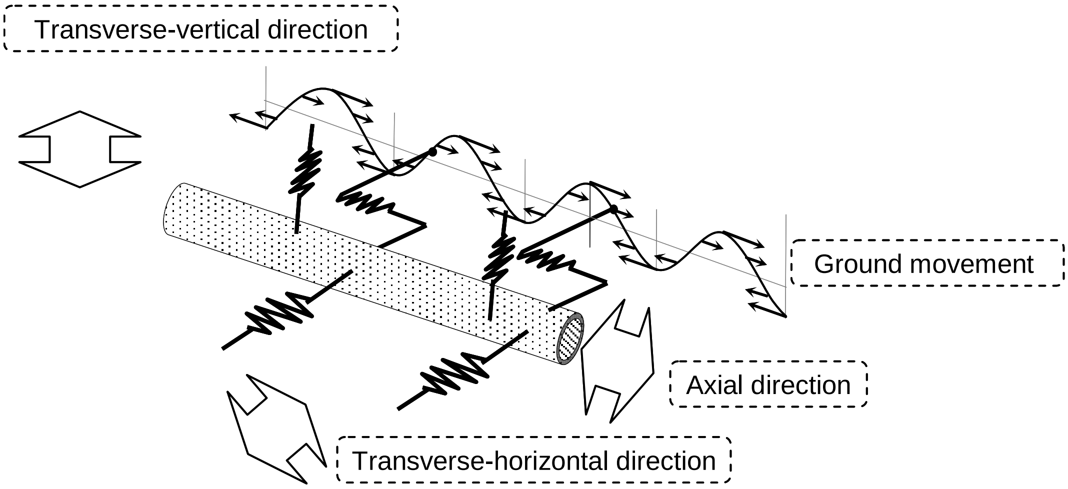


Figure 3: Image of soil-pipeline interaction

components in the axial, transverse-horizontal and transverse-vertical directions as shown in **Figure 3**.

The soil-pipeline interaction provided for in these seismic design guidelines was obtained from the results of full-scale experiments performed by Trautman and O'Rourke [3]. These experiments were carried out under regulated conditions. They pointed out that additional studies were needed to clarify the effects of the properties of the surrounding soil, such as soil moisture and soil density. Therefore, to realize a more rational design, Tokyo Gas has been conducting studies on the soil-pipeline interaction under various backfill conditions.

3. RECENT DEVELOPMENTS IN EVALUATION OF SOIL-PIPELINE INTERACTION

3.1 DEVELOPMENT OF ANALYTICAL METHOD TO EVALUATE EFFECT OF SOIL SURROUNDING PIPELINE ON SOIL-PIPELINE INTERACTION

The experimental studies required a lot of time and effort. Therefore, developing a highly accurate analytical method and carrying out parametric analysis for various soil properties are important to quantitatively evaluate of the soil-pipeline interactions. We have been developing an analytical method for evaluation soil-pipeline interaction. In this section, we first introduce the analytical model. We then compare the analytical result to that of experiment to show the validity of proposed analytical method.

(1) ANALYTICAL MODEL

(1-1) OBJECTIVE

The development of numerical analysis and its application to geotechnical engineering problems over the past 20 years have provided geotechnical engineers with an extremely powerful analysis tool. The most recent research work on numerical modeling of soil-pipeline interaction problems has been able to highlight the development of proper numerical tools to capture the real behavior of pipelines subjected to ground movements.

Although there have been effective contributions to the numerical modeling of soil-pipeline interaction in dry sand or fully saturated sand, research on pipeline behavior under partially saturated conditions is very limited. Because most pipelines are generally located above the water table, understanding of the pipeline response in unsaturated soil is essential in pipeline design owing to the higher effective stresses and strengths involved in the unsaturated soil due to suction. The past developed numerical method for the soil-pipeline interaction in dry or fully saturated soil, which was based on Classical saturated soil mechanics, does not provide the soil-pipeline interaction in unsaturated soil. Hence, the most of current research is strongly concentrated on numerically modeling the behavior of unsaturated soils and their interaction with buried pipelines.

(1-2) MODELING UNSATURATED SOIL BEHAVIOR

This section discusses the modeling of unsaturated soil behavior using the Mohr-Coulomb strength envelope.

First, we explain the Mohr-Coulomb strength envelope through FE analysis [4] of dry sand. It is a simple linear elastic-perfectly plastic model such as the one shown in **Figure 4.** This model is widely used in geotechnical engineering to simulate material responses under monotonic loading. The Mohr-Coulomb failure criterion assumes that failure occurs when the shear stress at any point in a material reaches a value that depends linearly on the normal stress in the same plane, as defined in Eq. 3-1.

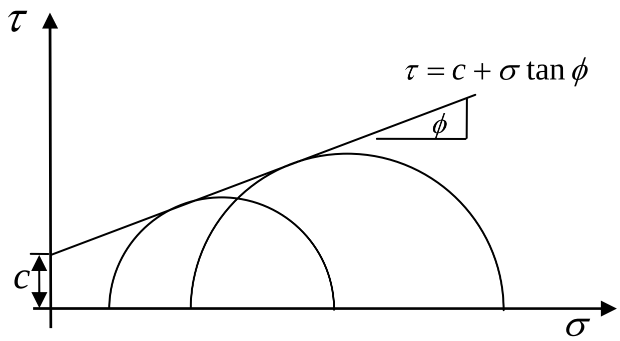


Figure 4: The Mohr-Coulomb failure criterion

$$\tau = c + \sigma \tan\phi \tag{3-1}$$

τ : shear stress

c : cohesion intercept

σ : total stress

ϕ : friction angle

The material constant c defines the cohesion yield stress for the hardening behavior of the material. The friction angle ϕ controls the shape of the yield surface deviatoric plane.

The state of stress in unsaturated soil is fundamentally different from that in dry or saturated soil. The dry or fully saturated soils are two-phase systems comprised essentially of soil particles and pore air or pore water (depending on dry or saturated condition). On the contrary, unsaturated soils are three phase systems consisting of solids (soil particles), liquid (pore water) and gas (pore air). The relative amounts and corresponding pressures of the pore water and pore air phases in unsaturated soil have a direct impact on inter-particle contact stresses and thus on the macroscopic mechanical behavior of the soil mass.

Thus it is necessary that the above behaviors are added in the Mohr-Coulomb strength envelope to apply the Mohr-Coulomb failure criterion to the modeling of unsaturated soils. Therefore, we adopted Bishop's effective stress concept [5] when modeling unsaturated conditions.

We then introduced the Mohr-Coulomb strength envelope discussed in conjunction with Bishop's concept and modified it to simulate the behavior of unsaturated soils. Bishop's concept converts a multiphase and multistress medium into a mechanically equivalent single phase and stress state continuum. It uses the following equation (Eq. 3-2) to define the effective stress.

$$\sigma' = (\sigma - u_a) + S(u_a - u_b) \qquad (3\text{-}2)$$

σ' : effective stress

S : water saturation

u_a : pore air pressure

u_b : pore water pressure

The value of suction represented $(u_a\text{-}u_b)$. The suction of the backfill can be measured by a tensiometer.

On the other hand, the Mohr-Coulomb strength envelope (Eq.3-1) is defined by the total stress. By expanding this equation to the equation of the effective stress, Eq.3-3 can be obtained.

$$\tau = c' + \sigma' \tan\phi' \qquad (3\text{-}3)$$

By substituting Eq.3-2 into Eq.3-3, we obtain Eq.3-4, which is the failure criterion for the unsaturated soil.

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_b)S\tan\phi' \qquad (3\text{-}4)$$

Table2-1 lists the input parameters for conducting the above analytical method to evaluate the behavior of unsaturated soils and their interaction with buried pipelines.

Table 3-1 Input parameters for unsaturated soil

parameters	unit	defined
c'	kPa	Effective cohesion
$\phi'\max$	deg	Peak friction
E	kPa	Young's modulus
ν		Poisson's ratio
S	%	Water saturation
$(u_a - u_b)$	kPa	Suction
k_{sat}	cm/s	Hydraulic conductivity

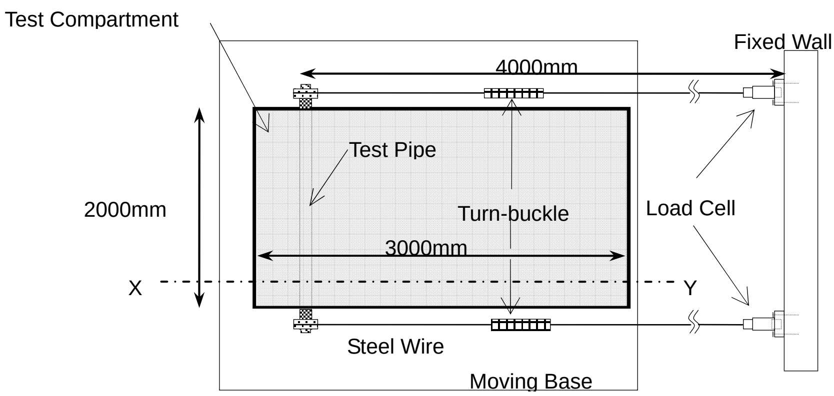
(2) ANALYSIS OF BURIED PIPELINES SUBJECTED TO TRANSVERSE-HORIZONTAL LOADING IN UNSATURATED SOILS

(2-1) EXPERIMENTAL OVERVIEW OF ANALYSIS OBJECT

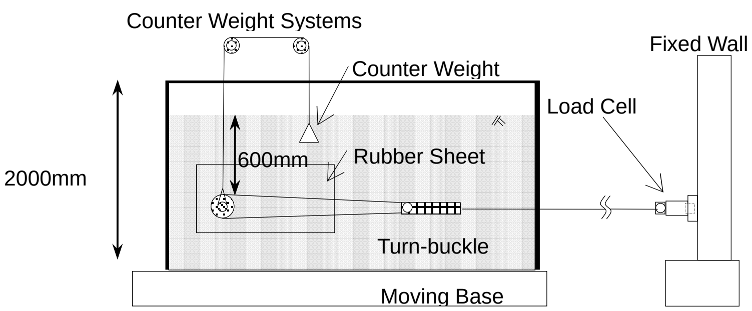
Full-scale experiments were conducted to obtain the reaction force for evaluation the soil-pipeline interaction in the transverse-horizontal direction. A test pipe having an outer diameter of 100mm was installed and backfilled in the test compartment on the shaking table. The inside dimensions of test comportment was 3.0m x 2.0m x 2.0m depth. The test pipe was installed at a 0.6m depth from the ground surface and pulled by hydraulic jacks through two steel wires. **Figure 5** shows the top and side views of the experimental setup. The test pipe was reinforced so that it would not be deformed during the experiments. Counterweight systems canceled out the extra weight of the test pipe.

The soil properties (e.g. moisture content) and compaction degree were important for this experiment. Therefore, we strictly controlled the ground conditions. The sand was placed and compacted in 0.15 m layers with strict control of in situ density. The filling was completed using a total of eight layers.

This experiment was performed under dense backfill conditions (in particular, dry density: 1.5 g/cm^3). The sand used for backfill was clean and is called “Chiba sand”. The moisture content was selected to average 15%.



(a) Top view



(b) Side view

Figure 5: Experimental setup

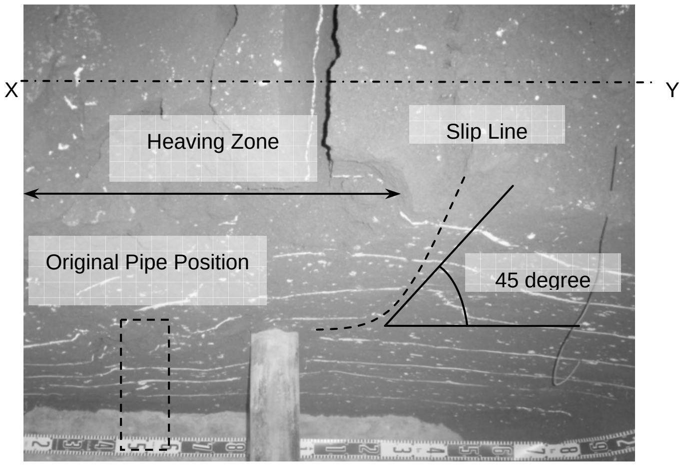


Figure 6: Ground deformation after experiment

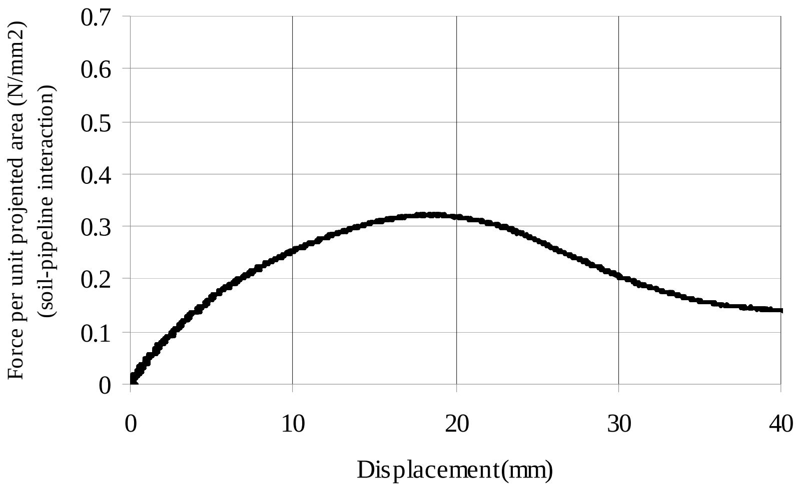


Figure 7: Soil-pipeline interaction

During the experiments, the test pipe was pulled for 0.4 m in the lateral direction. The rate of displacement of the hydraulic jacks was approximately 10 mm/s. As shown in **Figure 5**, the reaction force was measured with two load cells connected to the steel wires installed between the test pipe and fixed wall.

Figure 6 shows the plane view of the soil slip observed at Section X-Y, when about half of the sand in the soil box was removed after the experiment. As shown in **Figure 6**, the slip line reached the ground surface at an angle of about 45 degree to the horizontal direction.

Figure 7 shows the experimental results: the force per unit projected area versus relative displacement of the test pipe in the ground. The force gradually decreased after the relative displacement between the soil and test pipe reached the maximum force observed.

(2-2) ANALYTICAL RESULT

Figure 8 shows the analytical model for above experiment. In this study, the finite element analysis package ABAQUS was used. This solver is a general-purpose finite element analysis code that can be used to solve a wide range of linear and non-linear problems involving the static, dynamic, thermal, and electrical responses of components.

The pipe was pulled laterally by imposing equal lateral displacement on all pipe nodes and was set to move freely in the vertical direction.The wall boundaries were assumed to be smooth and supported only in the normal direction.

Figure 9 shows the comparison between the analytical results and the experimental results in terms of the force per unit projected area and displacement curve. **Figure 10** shows the shear stress distribution when the peak value of the force was observed.

The force-displacement curve obtained by FE analysis was in very good agreement with the experimental result for the maximum force and up to the maximum force as shown in **Figure 9**.

The soil-pipeline interaction is specified as a bilinear force-displacement relationship in the seismic design guidelines against both the seismic motion and ground liquefaction. That is, the soil-pipeline interaction increases with increasing the ground displacement, and then to be constant after the peak load in the guidelines.

In the case of the seismic motion, only the force-displacement relationship up to the peak load is important, because the ground displacement is relatively small. Therefore, the developed FE analytical method is applicable to the evaluation of the soil-pipeline interaction against the seismic motion. Because the effect of the properties of soil on the soil-pipeline interaction can be evaluated, this method enables us to realize the site specific design of pipeline against seismic motion.

On the other hand, the force-displacement relationship after the peak load is also important in the case of the PGD, because the ground displacement is relatively large. According to our experiment, the soil-pipeline interaction gradually decreased after the relative displacement between the soil and pipe reached to the peak load. This reduction is caused by a collapse of soil. This result suggests that the soil-pipeline interaction specified as a bilinear force-displacement relationship in the guidelines could be reduced. And this fact may enable us to conduct more rational design and maintenance of pipelines against PGD.

To clarify the effect of the properties of soil on the soil-pipeline interaction against PGD, it is necessary to develop newly analytical method because the developed FE analytical method cannot express the reduction of the soil-pipeline interaction due to collapse of soil. So, we now try to develop newly analytical method using a distinct element method, which can provide rational result in the evaluation of the soil-pipeline interaction against PGD.

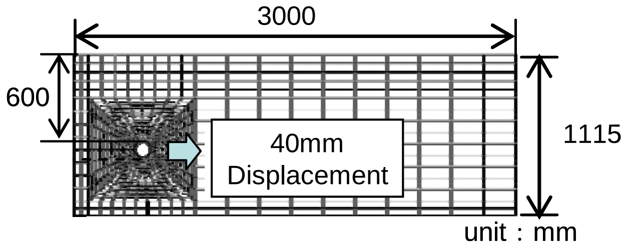


Figure 8: Analytical model for (2-1) experiment

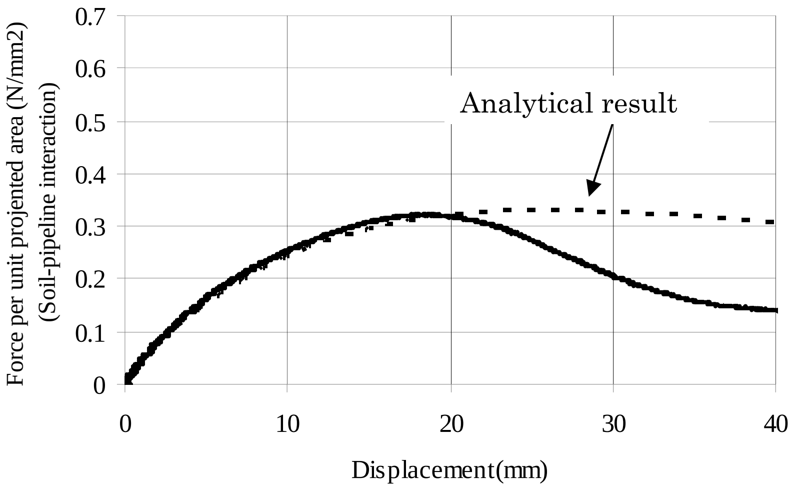


Figure 9: Comparison between experimental and analytical results

Figure 10: Shear-stress distribution when the peak value of the force was observed

3.2 THE EFFECT OF LIGHTWEIGHT BACKFILL ON REDUCTION OF SOIL-PIPELINE INTERACTION

For the pipelines constructed in areas where PGD is expected, deformability of pipeline should be improved either by increasing diameter, thickness or strength, or by reducing the soil-pipe interaction. In this section, we describe a method for reducing the soil-pipeline interaction. We investigated the effect of light weight backfill using EPS (expanded poly-styrene) on the reduction in soil-pipeline interaction by conducting full-scale experiment. Test pipe having an outer diameter of 100mm was buried in the ground, and was further pushed horizontally by 300 mm into the ground using a hydraulic jack. The reaction force was measured to evaluate the soil-pipeline interaction in the transverse-horizontal direction. **Figure 11(a)** shows a plan view of the experimental setup. Two tests were performed. Test 1 involved using backfill consisting only of compacted sand: in Test 2, we used the EPS backfill. Side views of both tests are shown in **Figures 11 (b) and (c)**, respectively.

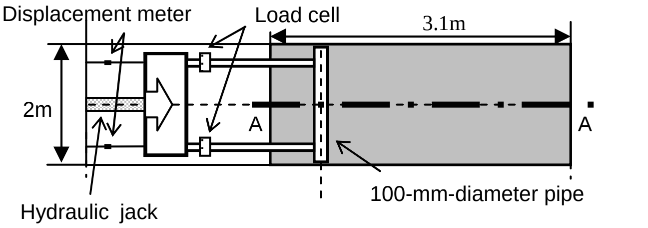
Figure 12 (a) shows the plane of the soil observed at section A-A, which is shown in **Figure 11 (a)**, after half of the sand in the test compartment from Test 1was removed. On the other hand, in Tests 2, the plane of the soil slip reached the EPS block, and then the slip occurred between the EPS and the sand, as shown in **Figure 12 (b)**. **Figure 13** shows the experimental results: normalized force per unit projected area was calculated from the force per unit projected area, which was adjusted so that the internal friction angles of the two tests were equal and normalized with the average of the maximum values recorded during Test 1. The maximum force recorded in Test 2, which used EPS blocks for backfill, was 54% of that in Test 1.

From these experimental results, the transverse-horizontal forces on the pipes with EPS backfill can be reduced to approximately half of that with normal (the sand) backfill. Therefore, the EPS backfill can remarkably enhance the earthquake-resistance of buried pipeline.

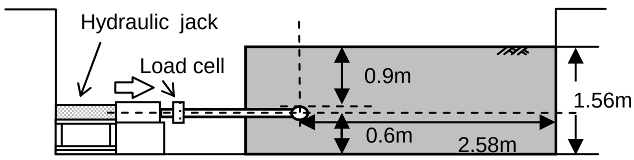
4. CONCLUSION

Tokyo Gas has been conducting intensive and comprehensive studies related to the seismic design of pipelines to realize more rational design and maintenance against strong seismic motions and subsequent PGD. This paper presents the results of the analytical study using FEA and full-scale experiments on soil-pipeline interaction.

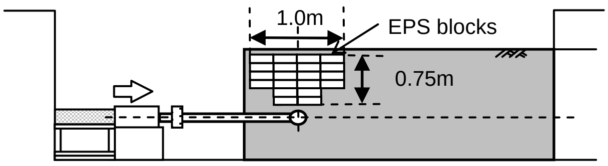
- The FE analytical method was developed to evaluate the soil-pipeline interaction in response under unsaturated conditions. The developed FE analytical results agreed reasonably well with the experimental results for both the soil-pipeline interaction and the deformation behavior of soil. This method enables us to evaluate the soil-pipeline interaction subjected to seismic motion under various types of soil.
- The effect of lightweight backfill on the reduction of soil-pipeline interaction was investigated by conducting full-scale experiments. When EPS blocks were used for backfill, the lateral forces on the pipes was reduced to approximately half that with normal backfill.



(a) Plan view



(b) Side view (Normal backfill)



(c) Side view (EPS backfill)

Figure 11: Experimental setup

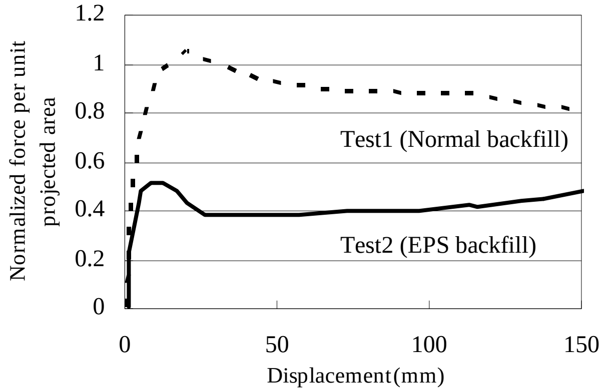
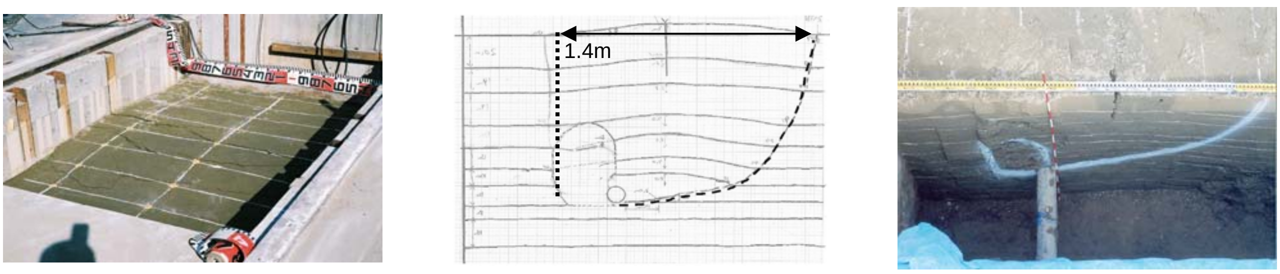
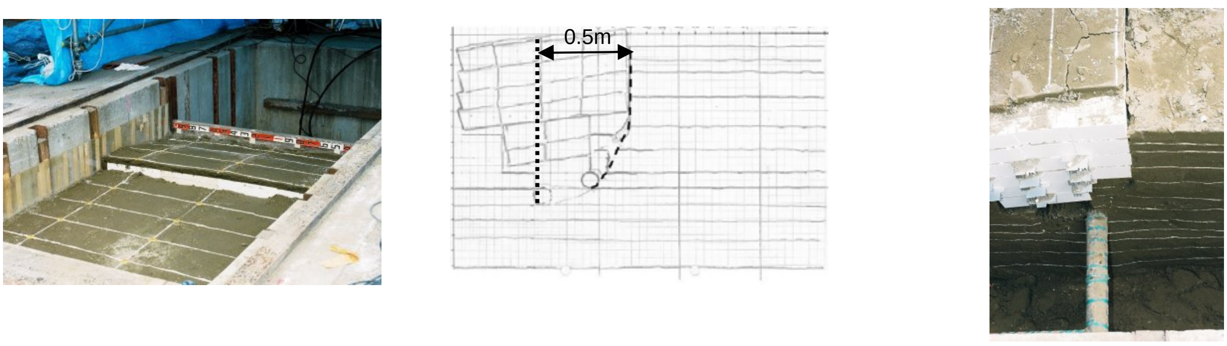


Figure 13: Experimental results showing effects of EPS backfill on soil-pipe interaction



(a) Slip surface (Normal backfill)



(b) Slip surface (EPS backfill)

Figure 12: Slip surfaces at section A-A' after tests

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