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ANALYTICAL STUDY ON SOIL-PIPELINE INTERACTION DUE TO LARGE GROUND DEFORMATION

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SUMMARY

Earthquake-induced Permanent Ground Deformation (PGD), occurring as a surface fault deformation, liquefaction-induced soil movements, and landslides, can significantly affect underground lifelines, such as buried gas and water pipelines. 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 soil. 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 decreased when the relative displacement between soil and pipe is 0.1 m in the case of dense sand for backfill. In the case of PGD, therefore, it is expected that the soil-pipe interaction is much smaller when the ground displacement is a few meters due to the collapse of the soil.

In this study, the effect of the decrease in soil-pipe interaction due to large ground deformation on the earthquake-resistance of buried pipelines was investigated. Finite element analyses were conducted to evaluate the decrease in the soil-pipe interaction due to large ground deformations. The FE results, which reasonably agreed with the ASCE recommendation based on the research of Trautmann and O'Rourke for both the maximum dimensionless force and the displacement, showed a gradual reduction as the relative displacement between the soil and pipe increases with respect to the soil-pipe interaction.

The effect of the decrease in the soil-pipeline interaction on the large deformation behavior of buried pipelines was also investigated by parametric analyses. For a 400-mm-diameter pipeline with a 90-degree bend subjected to PGD, the decrease in the soil-pipe interaction due to a large ground deformation had a significant effect on the strain reduction of the pipeline.

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INTRODUCTION

During earthquakes, underground lifelines such as buried gas pipelines can be affected by the surrounding soil. To maintain their function as lifelines supporting people's lives, and at least prevent disasters caused by leakage of the contents, it is important to consider the effect of earthquakes in the design and maintenance of such lifelines.

Earthquake-induced Permanent Ground Deformation (PGD), occurring as a surface fault deformation, liquefaction-induced soil movements, and landslides, can significantly affect underground lifelines, such as buried gas and water pipelines. There is substantial evidence of gas and water supply pipeline damage caused by PGD from past major earthquakes, such as the 1906 San Francisco [1], the 1964 Niigata, the 1971 San Fernando [1], the 1979 Imperial Valley, the 1983 Nihonkai-chubu [2], the 1989 Loma Prieta, the 1994 Northridge [3], and the 1995 Hyogoken-nanbu [4] earthquakes. More recent earthquakes, including the 1999 Kocaeli and Duzce earthquakes in Turkey, and the 1999 Chi-chi earthquake in Taiwan [5], have provided additional evidence for the importance 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 soil. 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 [6], however, showed that the force gradually decreased when the relative displacement between the soil and pipe is 0.1 m in the case of dense sand for backfill. In the case of PGD, therefore, it is expected that the soil-pipe interaction is much smaller when the ground displacement is a few meters due to collapse of the soil.

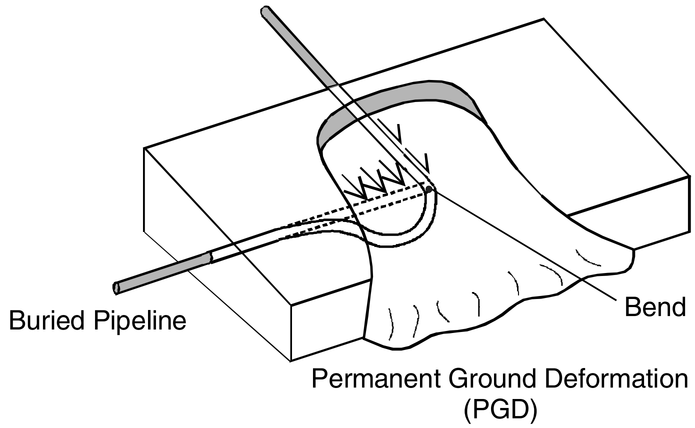
In this paper, the effect of the decrease in soil-pipe interaction due to large ground deformations on the earthquake-resistance of buried pipelines was investigated. Finite element analyses were conducted to evaluate the decrease in the soil-pipe interaction due to a large ground deformation. The effect of the decrease in the soil-pipeline interaction on the large deformation behavior of buried pipelines was also investigated by parametric analyses.

FINITE ELEMENT ANALYSIS ON SOIL-PIPE INTERACTION IN LATERAL DIRECTION

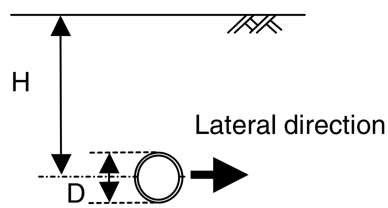
Analytical model

To evaluate the deformation behavior of pipelines subjected to PGD as shown in Figure 1 (a), it is essential to evaluate the soil-pipe interaction in the lateral direction. A finite element analysis was conducted on the soil-pipe interaction in the lateral direction to calibrate it with previous research. To simulate the soil-pipe interaction in the lateral direction due to the relative displacement between the soil and pipe, the pipe was displaced in the horizontal direction in the analytical model, as illustrated in Figure 1 (b).

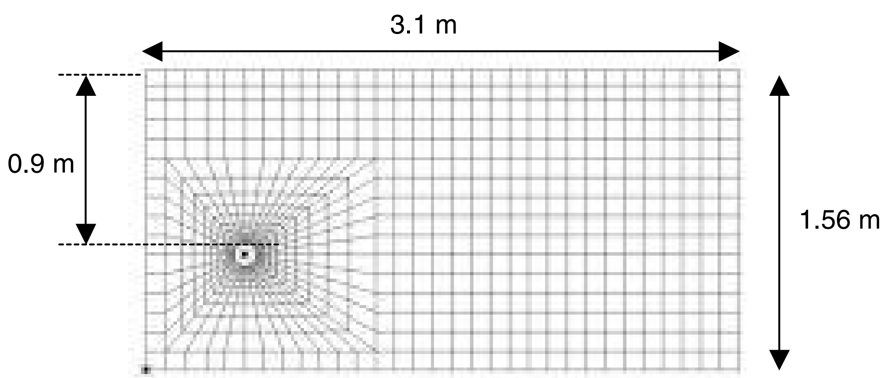
Figure 1 (c) shows the analytical model for the case of 100-mm-diameter pipe and the cover depth of 0.9m. A 2-dimensional model was used as proposed by Yimsiri et al.[7]. The dimensions of the model are 3.1 m in length and 1.56 m in depth as shown in Figure 1 (c).



(a) PGD effect on a buried pipeline with a bend



(b) Direction of pipe movement in the ground



(c) Analytical model (100-mm-diameter pipe with a cover depth of 0.9 m)

Figure 1 Analytical model

The soil used in the model is called "Chiba Sand", which is a typical sand used as backfill for pipelines in Japan. Its properties are summarized in Table 1 and they satisfy the standard for backfill sand specified by the Bureau of Construction of the Tokyo Metropolitan Government. The grain size distribution for the Chiba Sand is shown in Figure 2.

The Mohr-Coulomb model was used in the analytical model. To obtain the parameters in the model, triaxial compression tests were conducted for several confining pressures, dry unit weights and strain ratios. Figure 3 shows the relationship between the peak friction angle and the dry unit weight obtained from the triaxial tests for Chiba Sand with strain ratios of 5%/min and 0.1%/min. Young's elastic modulus is determined based on the results of various triaxial data with the assumption that Young's modulus is a power function of the effective confining pressure with the exponent being 0.5 [7, 8]. The elastic

Poisson's ratio is assumed to be 0.3. The dilation angle was estimated using the relationship between the peak friction angle and the critical state angle proposed by Bolton [9].

ABAQUS/Standard version 6.4 was used as a solver. Four-node, full-integration continuum elements were used for the soil. The pipe was modeled using rigid elements. The analysis was performed in plane strain and dry conditions. The friction between the pipe and the surrounding soil was modeled by contact simulation in which the slip and separation between the pipe and soil is allowed. The friction coefficient between the pipe and soil was set at 0.1. Gravity was applied for the soil as well. The peak friction angle of 46.5 degrees, which is very dense sand, was assumed in the analysis.

Table 1 Physical properties of Chiba Sand

Specific gravity (Mg/m^3)		2.65
Grain size distribution	Gravel (%)	0
	Sand (%)	96.6
	Silt (%)	3.4
Maximum dry unit weight (kN/m^3)		16.0
Optimum water content (%)		17.2

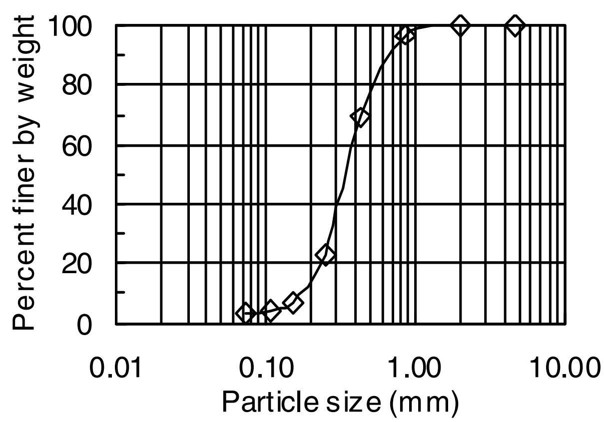


Figure 2 Grain size distribution of Chiba Sand

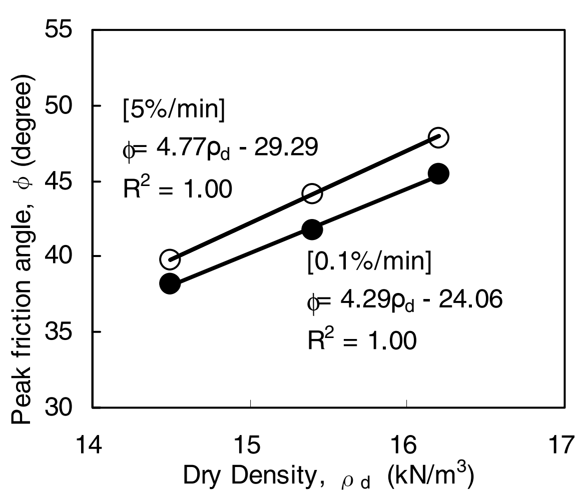
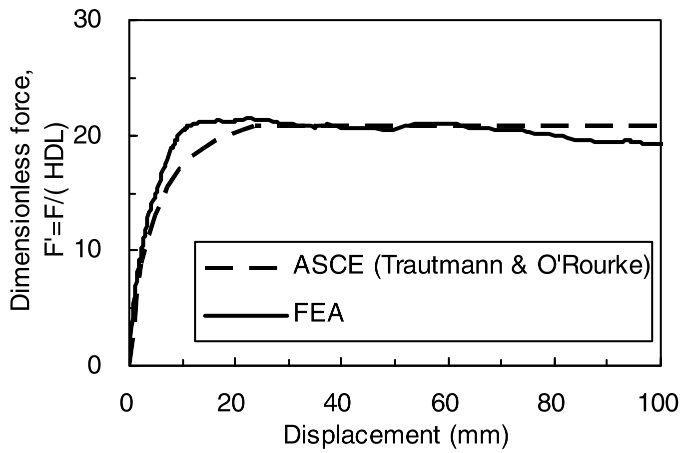


Figure 3 Relationship between dry unit weight and peak friction angle

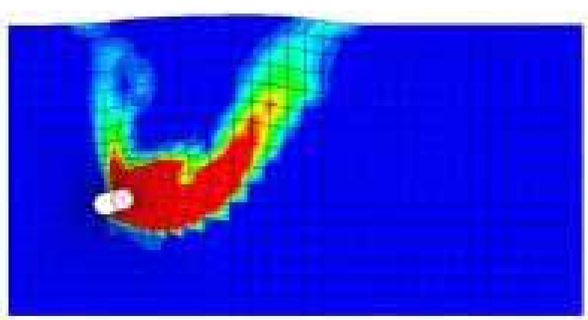
Analytical results

Figure 4 (a) shows the comparison between the analytical results and the recommendation in the ASCE (American Society of Civil Engineers) guideline [10] based on the research conducted by Trautmann and O'Rourke [6] in the form of a dimensionless force-displacement curve. Here, the dimensionless force is calculated as a force per unit projected area normalized with the vertical pressure. The FE result agreed reasonably well with the ASCE recommendation based on the research of Trautmann and O'Rourke for both the maximum dimensionless force and the displacement. This agreement was also investigated by Yimsiri et al. [7] for the simulation by the experiments conducted by Trautmann and O'Rourke [6].

Figure 4 (b) shows the strain distribution and the deformed shape of the analytical result when the relative displacement between the soil and the pipe is 100 mm. Although a discontinuous strain distribution was observed due to the course mesh, the deformation had reasonable agreement with the deformation observed by Trautmann and O'Rourke [6] or the soil deformation and shear surface observed by the authors [11], as shown in Figures 5 (a) and (b), respectively.

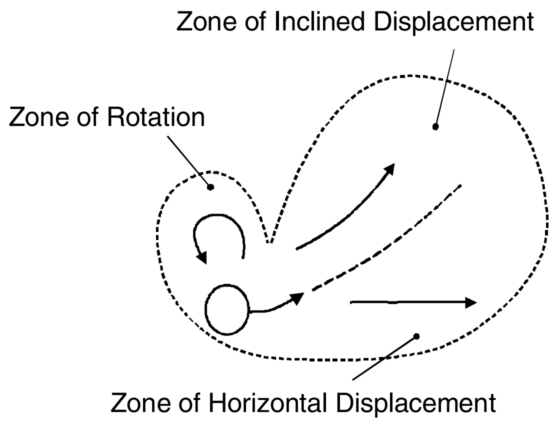


(a) Comparison between the analytical result and the recommendation in ASCE guideline



(b) Strain distribution (Displacement = 100 mm)

Figure 4 Analytical result



(a) Soil movement observed in the experiments conducted by Trautmann and O'Rourke [6]

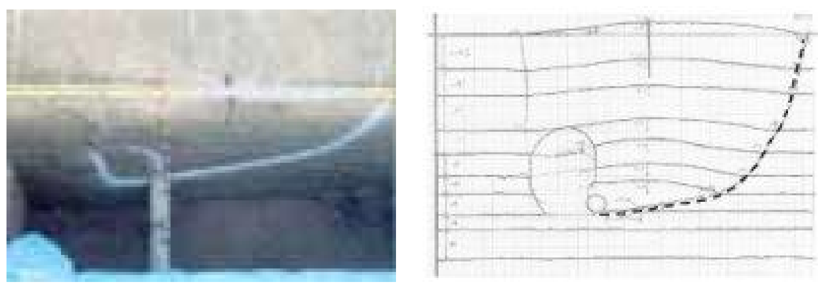

(b) Soil deformation and failure surface observed in the experiments [11]

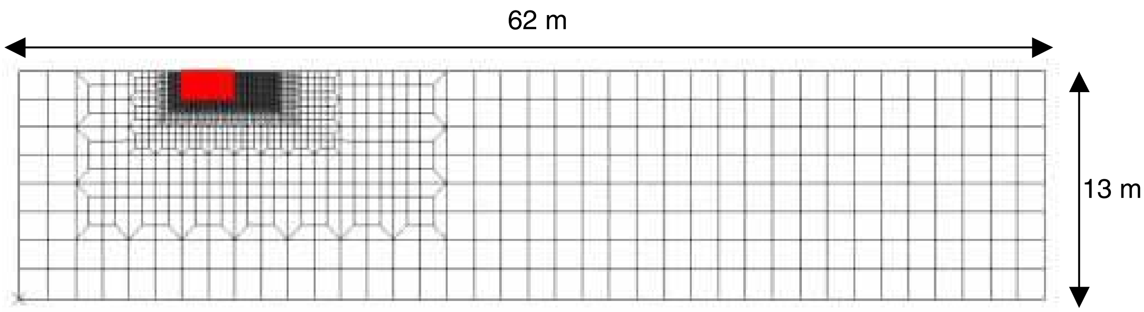
Figure 5 Deformation behavior of soil in previous research

Decrease in soil-pipe interaction

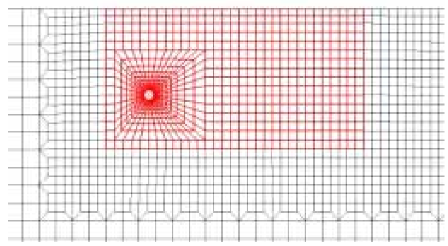
To investigate the effect of the size of the analytical model, an FE analysis was conducted using an analytical model with an extended area. Figure 6 (a) shows the entire model. The red mesh in the figure is the size of the model that was used in the previous section. Figure 6 (b) is an enlarged view around the red mesh.

Figure 7 (a) shows the strain distribution of the analytical result for a displacement of 100 mm. The strain distribution obtained from the analytical model with the extended area agreed well with the result from the smaller model shown in Figure 1 (c). Figure 7 (b) shows the comparison among the results of the two analytical models and the recommendation by the ASCE guideline [10] in the form of a dimensionless force-displacement curve. The two models had reasonable agreement with the recommendation set forth in the ASCE guideline for the maximum dimensionless force. Based on these results, the model shown in Figure 1 (c) is large enough to evaluate the soil-pipe interaction behavior for the 100-mm-diameter pipe with a cover depth of 0.9 m.

Figure 7 (b) illustrates an important finding in the soil-pipe interaction for a large displacement. The analytical results of both models showed a gradual decrease as the relative displacement between the soil and the pipe increases as shown by the arrow in Figure 7 (b). This trend was also observed in the experiments conducted by Trautmann and O'Rourke [6], the joint collaborative project on soil-pipe interaction among Tokyo Gas, Advantica, TransCanada Pipelines, Gaz de France, Italgas and the Geological Survey of Canada, and the authors [11] when using a dense sand for backfill.

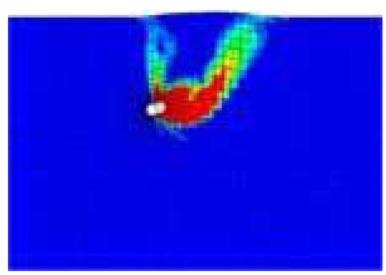


(a) Overall view

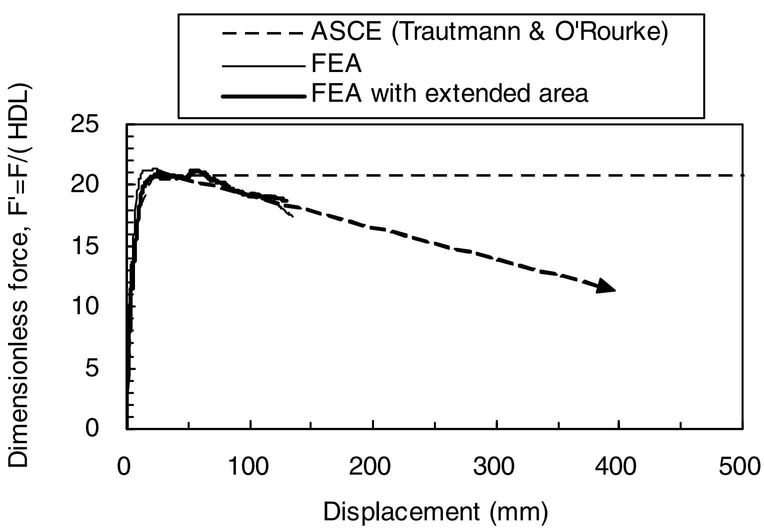


(b) Enlarged view

Figure 6 Analytical model with extended area



(a) Strain distribution (Displacement = 100 mm)



(b) Comparison among the analytical results and the ASCE recommendation

Figure 7 Analytical results of decrease in soil-pipe interaction

EFFECT OF DECREASE IN SOIL-PIPE INTERACTION ON LARGE DEFORMATION BEHAVIOR OF PIPELINES SUBJECTED TO PGD

Analytical model

FE analyses were conducted in order to evaluate the effect of the decrease in the soil-pipe interaction observed in the analytical results in the previous section on large deformation behavior of buried pipelines.

Gas and other types of pipelines must often be constructed to rapidly change direction to avoid other underground facilities or to adjust to the shape of roads under which the pipelines are buried. In such cases, a pipeline is installed with an elbow or a bend that can be fabricated in order to change the direction from 90 to a few degrees. Because bends are locations where flexural and axial pipeline deformations are restrained, concentrated strains can easily accumulate at these bends in response to PGD, as shown in Figure 1 (a). Therefore, a model of a buried pipeline with a bend subjected to PGD, as shown in Figure 8, is assumed for evaluation of the effect of the decrease in the soil-pipe interaction.

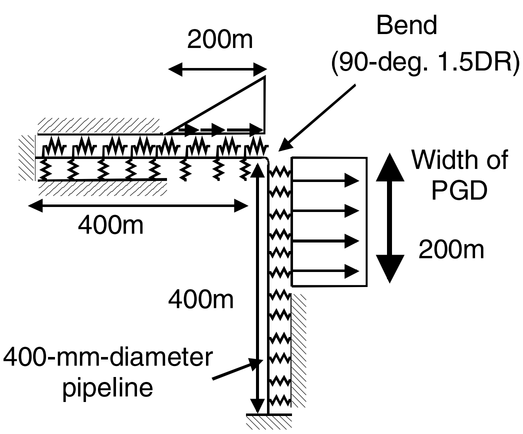
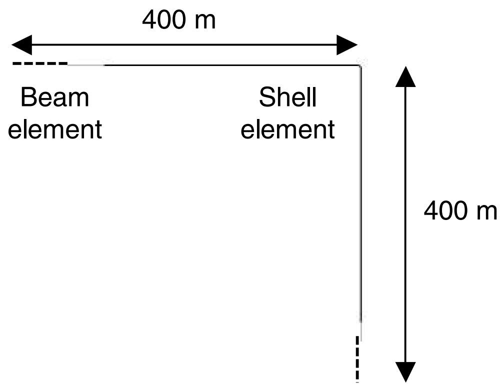


Figure 8 Assumed model of a buried pipeline with a bend subjected to PGD

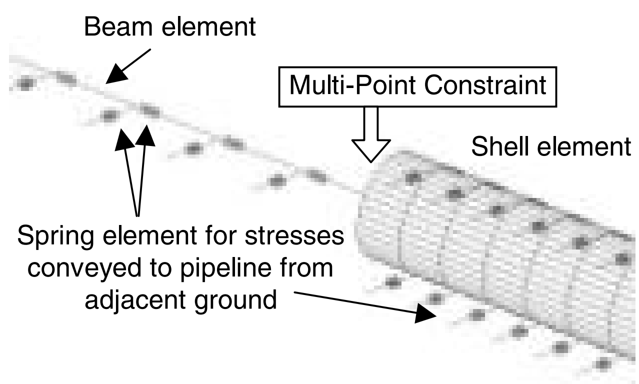
A modeling technique called HYBRID MODEL was developed for simulating a large-scale pipeline and bend response to PGD in the previous studies [12, 13]. The model uses shell elements for the bend and its neighboring parts where large, localized strains occur. As shown in Figure 9 (a), the shell elements are located over a distance equal to 40 times the diameter from the center point of the bend. The shell elements are linked to beam elements that extend beyond the distance of 40 times the diameter. Deformation continuity between the shell and beam elements is enforced by the use of the Multi-Point Constraint in ABAQUS, as shown in Figure 9 (b). The model, which is now being used in the design guideline for pipelines in Japan [14], was verified and calibrated with large-scale experiments of PGD effects on the large deformation behavior of steel pipelines with bends in a previous study [15].

A 400-mm-diameter pipeline with a 90-degree bend was used to evaluate the effect of the decrease in the soil-pipe interaction on its large deformation behavior subjected to PGD, as shown in Figure 8. API 5L X60 steel was used for both the straight pipes and the bend using the same analytical model from the previous study [16].

The pipeline was modeled with isotropic shell elements with reduced integration points. ABAQUS was used as a solver for the analyses with geometric nonlinearity and large strain formulation. The von Mises criterion and associated flow rule were applied to the model. Since the straining is in the same direction in the strain space throughout the analyses, isotropic hardening was used in the model.



(a) Analytical model around bend

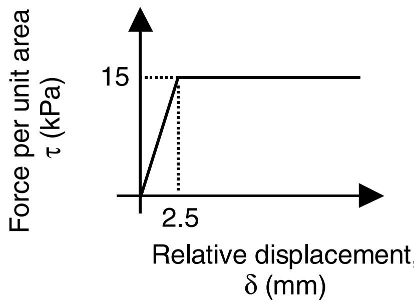


(b) Modeling for connection between shell elements and beam elements

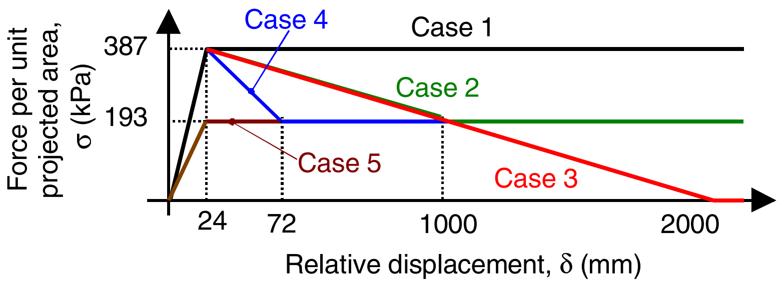
Figure 9 HYBRID MODEL used for analyses of buried pipelines

The soil-pipe interaction was modeled with discrete spring elements in both the longitudinal and circumferential directions for the shell elements, and in the longitudinal direction for the beam elements, as shown in Figure 9 (b). The force-displacement relationships were modeled in accordance with the JGA guideline [17] in the axial direction. Figure 10 (a) shows the force per unit area vs. relative displacement plot used to model soil-pipe interactions in the axial direction. The model in the axial direction was calibrated with full-scale experiments conducted by Kobayashi et al. [18].

Figure 10 (b) shows the force per unit projected area vs. relative displacement plot in the lateral direction. By comparing the case with a bilinear curve, which is defined as Case 1 in Figure 10 (b), the effect of the decrease in the soil-pipe interaction due to large ground deformation was modeled with the same value for the peak but a decreased value for the large displacement on the force per unit projected area, which is defined as Case 2 in Figure 10 (b). The rate of decrease is determined according to the extrapolation of the analytical results shown in Figure 7 (b), and the residual value was assumed to be half of the peak value. To investigate the effect of the residual value, the case which has the same rate of decrease and zero of the residual value, Case 3, was conducted. Parametric analysis was conducted as well to investigate the effect of the rate of decrease, as plotted as Case 4 in Figure 10 (b). As a bench mark, the case with a peak value, which is same as the residual value for Cases 2 and 4, was also conducted and called Case 5, as shown in Figure 10 (b).



(a) Axial direction



(b) Lateral direction

Figure 10 Model of soil-pipe interaction for 400-mm-diameter pipe with cover depth of 1.8 m

Analytical results

Figure 11 shows the analytical results in which the maximum strain in either the longitudinal or circumferential direction is plotted vs. the ground displacement. When the ground displacement is 3 m, the maximum strain of Case 1, which is the case without the decrease in the soil-pipe interaction, was 10.1%, whereas that of Case 2 with the decrease in the soil-pipe interaction was 7.1 %, which was a 30 % of reduction. Figures 12 (a) and (b) shows the strain distribution when the ground displacement is 3 m for Case 1 and 2, respectively. Relatively large strain was observed at the bends for both cases, but the magnitude of strain was reduced due to the decrease in soil-pipe interaction.

The maximum strain of Case 3, which residual value of the soil-pipe interaction is zero when the relative displacement between soil and pipe is 2 m, was 6.6 %. With the rate of the decrease in soil-pipe interaction for Cases 2 and 3, the residual value had little effect on the deformation of the pipeline when the ground displacement is 3 m.

The rate of the decrease in the soil-pipe interaction had significant effect on the pipeline deformation, as shown in the comparison between Cases 2 and 4 in Figure 11. The maximum strain was 7.1 % and 5.7 % for Cases 2 and 4, respectively, and the rate of the decrease in the soil-pipe interaction had 19 % reduction effect for these cases. The maximum strain of Case 4 was very close to that of Case 5, which was 5.6 %. These analytical results showed that the rapid increase and subsequent rapid decrease in the soil-pipe interaction such as Case 4 shown in Figure 10 had little effect on the maximum strain of the pipeline subjected to PGD.

For these specific cases involving a 400-mm-diameter pipeline with a 90-degree bend and a cover depth of 1.8 m, the rate of the decrease as well as the decrease in the soil-pipe interaction due to large ground deformation shown in Figure 11 had significant effects on the strain reduction on the pipeline. To quantify the effect of various diameters, cover depth, friction angle, residual value or rate of the decrease in the soil-pipe interaction, further investigations are needed.

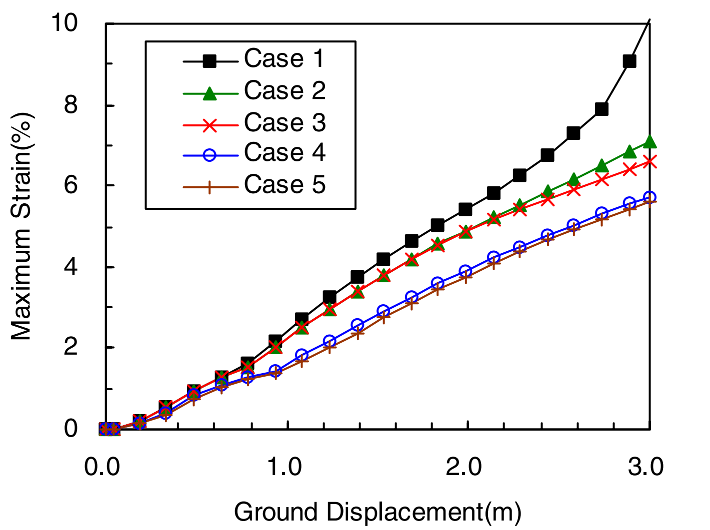
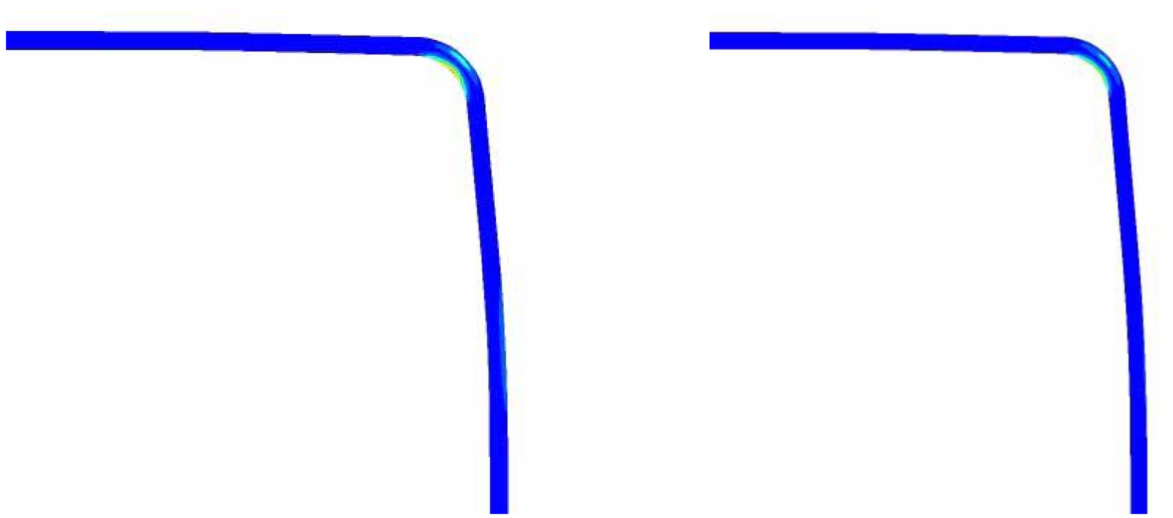


Figure 11 Analytical results on the effect of decrease in soil-pipe interaction on deformation behavior of a buried pipeline with a bend



(a) Case 1 (b) Case 2

Figure 12 Strain distribution of the pipeline at the ground displacement of 3 m

CONCLUSIONS

This paper investigated the effect of a decrease in soil-pipe interaction due to a large ground deformation on the earthquake-resistance of buried pipelines. Finite element analyses were conducted to evaluate the decrease in the soil-pipe interaction in the lateral direction due to a large ground deformation. The effect of the decrease in the soil-pipe interaction on the large deformation behavior of buried pipelines was also investigated using parametric analyses. The following conclusions are drawn from this study:

(1) The FE result reasonably agreed with the ASCE recommendation based on the research of Trautmann and O'Rourke for both the maximum dimensionless force and the displacement.

(2) The analytical results showed a gradual decrease as the relative displacement between the soil and pipe increases.

(3) The decrease in the soil-pipe interaction due to a large ground deformation had a significant effect on the strain reduction on the pipeline subjected to PGD.

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