13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2389

A STUDY ON EARTHQUAKE-RESISTANT DESIGN FOR BURIED PIPELINE USING LIGHTWEIGHT BACKFILL

Takashi Sakanoue[1] and Koji Yoshizaki[2]

SUMMARY

Earthquake-induced Permanent Ground Deformation (PGD) which occurs as surface fault, liquefaction-induced soil movements, and landslides, can cause serious damage to underground lifelines such as buried pipelines. For the pipelines constructed in areas where such PGD is expected, the pipe stiffness should be increased with larger diameter, thickness or strength, or the soil-pipe interaction should be reduced. In this paper, the effect of lightweight backfill on reduction of soil-pipe interaction was evaluated for earthquake-resistant design.

Full-scale experiments were conducted to evaluate the effect of lightweight backfill for reduction of soil-pipe interaction. Two kinds of material were used for lightweight backfill; EPS(Expanded Poly Styrene) and EGW(Expanded Glass Waste). 100-mm-diamter pipeline was buried in the ground assuming a pipeline buried under roads. Then, pipeline was pushed into the ground horizontally with a hydraulic jack and the reaction force was measured. The result showed that lightweight backfills had 56% and 34% reduction, respectively, on the soil-pipe interaction in the case that the cover-depth is 0.9m.

Furthermore, 400-mm-diamter pipeline with a 90-degree elbow was used to evaluate the effect of lightweight backfill on large deformation behavior subjected was also evaluated using Finite Element analytical model with the obtained reduction in soil-pipe interaction. The result showed that lightweight backfill had 58% and 47% reduction, respectively, on the strain of the pipelines deformation.
As a result, lightweight backfill had significant effect for enhancement of earthquake-resistance of buried pipelines.

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 [1], the 1964 Niigata, the 1971 San Fernando [1], the 1979 Imperial Valley, the

[1] Researcher, Tokyo Gas Co., Ltd., 1-7-7 Suehiro-cho, Tsurumi-ku, Yokohama, 230-0045, JAPAN. E-mail: sakanoue@tokyo-gas.co.jp
[2] Senior Researcher, Tokyo Gas Co., Ltd., 1-7-7 Suehiro-cho, Tsurumi-ku, Yokohama, 230-0045, JAPAN. E-mail: yoshi@tokyo-gas.co.jp

1983 Nihonkai-chubu [2], the 1989 Loma Prieta, the 1994 Northridge [3] and the 1995 Hyogoken-nanbu [4] earthquakes. In areas where such PGD is expected, it is desirable to take to prevent pipeline damage by increasing the diameter or stiffness. However, it is difficult to predict such areas exactly.

Generally, the soil-pipeline interaction is related to the weight of the soil above the pipeline [5,6]. Therefore, by lightening the weight, reduction of the soil-pipeline interaction can be expected.

In this paper, the effect of lightweight backfill on reduction of soil-pipeline interaction was evaluated experimentally. To investigate the effect of lightweight backfill, full-scale experiments were conducted. 100-mm-diameter pipeline was buried in the ground simulating a pipeline buried under roads. The pipeline was then pushed into the ground horizontally with a hydraulic jack, and the reaction force was measured. EPS and EGW were used as lightweight backfill in the experiments. EPS is widely used for embankment on soft ground or sloped areas where landslides are expected [7]. EGW is a newly developed lightweight ground material made of glass bottle waste, which is used as reinforced soil on soft ground for construction sites [8].

Part of this work has been already presented in 22ND International Conference on Offshore Mechanics and Arctic Engineering (ASME, 2003) [13].

FULL-SCALE EXPERIMENTS

Experimental procedures

Full-scale experiments were conducted to evaluate the effect of lightweight backfill on reduction of soil-pipeline interaction. A test pipe that was 100mm in diameter was installed and backfilled in a test compartment which had inside dimensions of 3.1m by 2.0m by 1.56m deep. The test pipe was installed at a 0.9m depth from the ground surface and pushed into the compartment using a hydraulic jack through two 65-mm-diameter pipes. Figure 1 (a) shows a top 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.

Three kinds of tests, Test 1, Test 2, Test 3, were conducted. Test 1 was performed with backfill of compacted sand. The sand used for backfill is called “Chiba Sand”, which is a clean sand. The properties are summarized in Table 1 and satisfy the standard for backfill sand specified by the Bureau of Construction of the Tokyo Metropolitan Government[9]. The grain size curve for the sand is shown in Figure 2. The sand was placed and compacted in 0.15m lifts with strict control of water content and in situ density. The side view of the setup for Test 1 is shown in Figure 1 (b).

For Test 2, the procedures for the placement of sand up to a depth of 0.76m were the same as in Test 1. Above the test pipe, EPS blocks with dimensions of 0.5m by 0.25m by 0.125m were placed on the assumption that the trench is 1.0m in width as shown in Figure 1 (c). The physical properties of the EPS blocks are shown in Table 2.

For Test 3, the procedure for the placement of sand up to a depth of 0.76m was the same as in Test 1. EGW was then placed at 0.1m above the test pipe and compacted in 0.15m lifts with strict control of in situ density as shown in Figure 1 (d). Figure 3 shows the grains of EGW before the test. The physical properties of EGW are summarized in Table 3. Here, the ultimate compressive strength listed in Table 3 is a property of a block of EGW, which is provided by the supplier. The grain size curves for EGW before and after the compaction are shown in Figures 4 (a) and (b), respectively. During the compaction, the grains of EGW were crushed due to the vibration energy.

During the experiments, the pipe was pushed into the test compartment for 0.3m in the horizontal direction. The rate of displacement of the hydraulic jack was approximately 3mm/sec. As shown in Figure 1, the reaction force was measured with two load cells to and the displacement of the pipe was measured with the two displacement meters.

Table 4 summarizes the experimental conditions of the sand before for the tests. In this table, internal friction angles obtained from triaxial compression tests with a strain rate of 5%/min. were determined based on the dry unit weight using the relationship shown in Figure 5.
Before each test, two plate loading tests were conducted at point X and Y shown in Figures 1 (a) and (b) to evaluate the bearing capacity of the backfill. Table 8 shows the results of the plane loading tests.

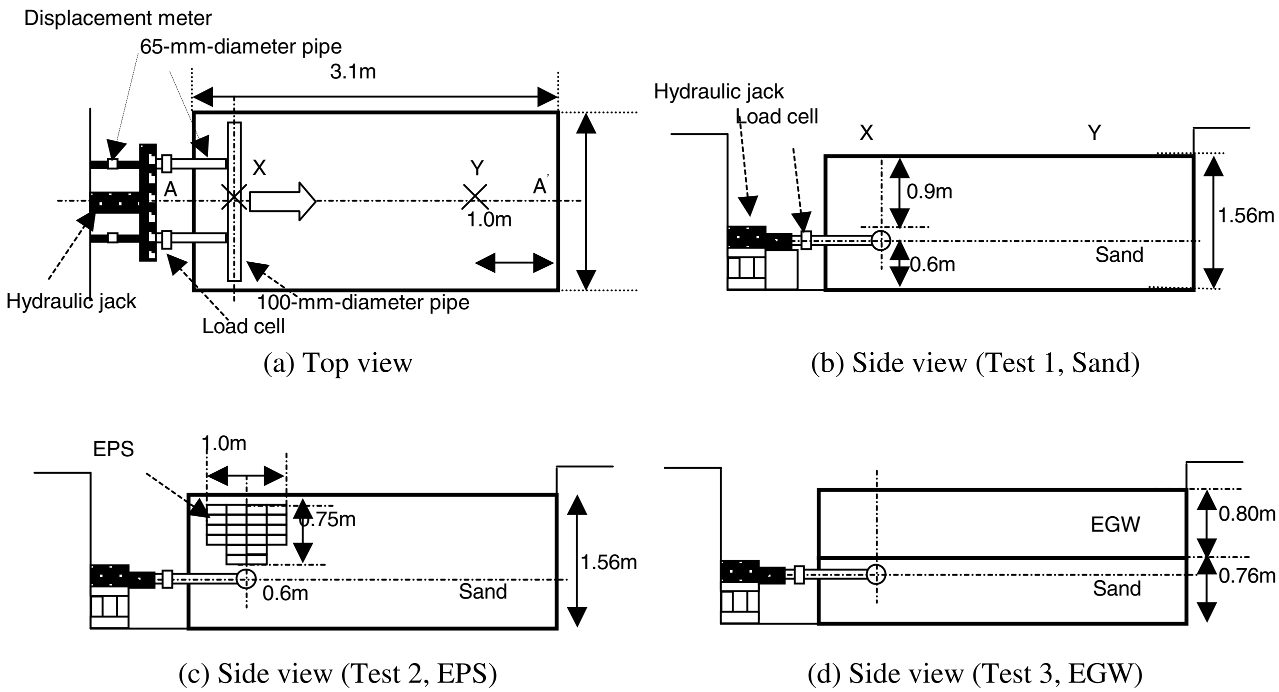


Figure 1 Experimental setup

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)		17.0
Optimum water content (%)		17.2

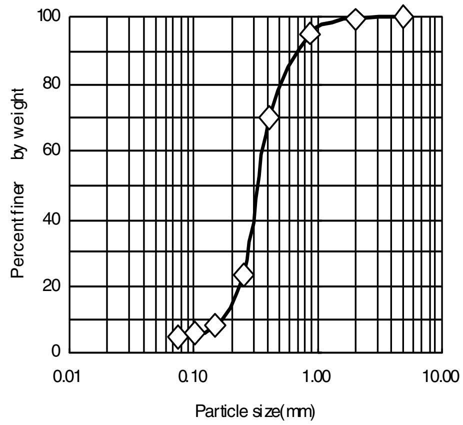


Figure 2 Grain size distribution of Chiba Sand

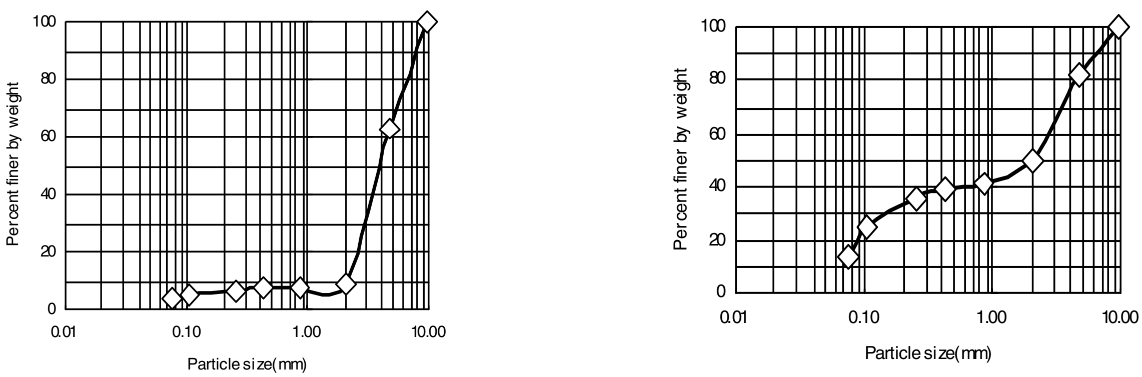
Table 2 Physical properties of EPS block

Unit weight (kN/m^3)	0.3
Ultimate compressive strength (kN/m^2)	180
Allowable compressive stress (kN/m^2)	90
Allowable temperature (degrees Celsius)	80

Figure 3 Grains of EGW

Table 3 Physical properties of EGW

Unit weight (kN/m^3)	3.9
Ultimate compressive strength (kN/m^2)	300~400



(a) Before the compaction

(b) After the compaction

Figure 4 Grain size distribution of EGW

Table 4 Experimental conditions

Test number		Test1	Test2	Test3
Backfill		Sand	EPS	EGW
Sand	Water content (%)	16.6	17.6	19.1
	Wet unit weight (kN/m^3)	17.8	18.1	18.6
	Dry unit Weight (kN/m^3)	15.2	15.4	15.6
	Degree of compaction (%)	96	96	98
	Internal friction angle (degree)	41.3	42.2	43.7

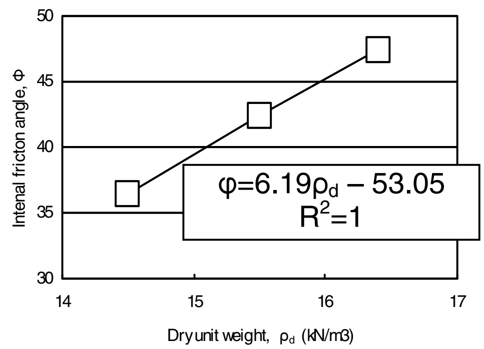


Figure 5 Relationship between dry weight and internal friction angle

Table 5 Results of plane loading test

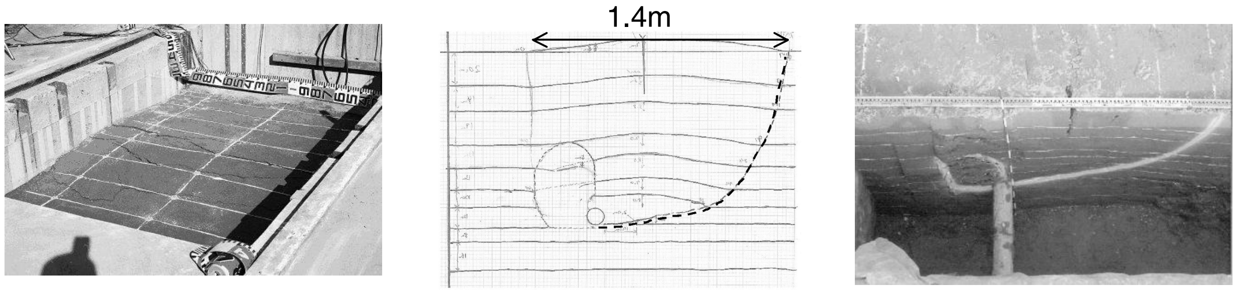
		Test 1	Test 2	Test 3
Coefficient of subgrade reaction (MN/m^3)	X	56.5	14.1	20.0
	Y	73.8	80.0	28.1

Experimental results

Figure 6 (a) shows the ground surface of the test compartment after Test 1. Figures 6 (b) and (c) show the plane of soil slip observed at Section A-A', which is shown in Figure 1 (a) when the about half of the sand in the test compartment was removed after the test. In Figure 6 (b), the doted line is the observed slip line. The horizontal distance between the original pipe position and the slip surface which reached the ground surface was 1.4m.

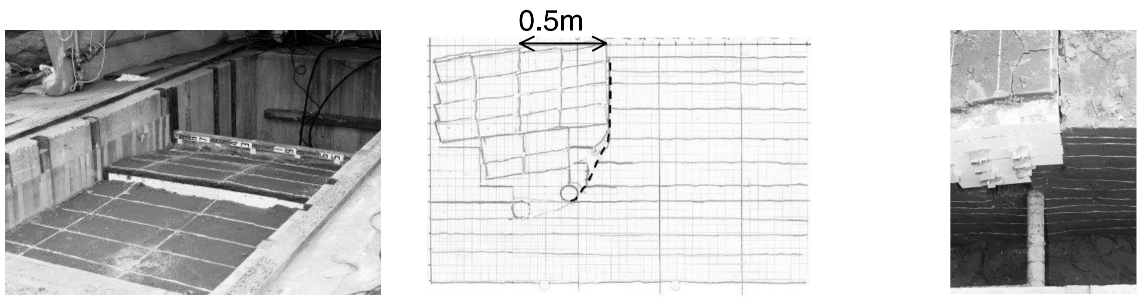
Figures 7 (a), (b), (c) show the ground surface of the test compartment and the plane of soil slip observed at Section A-A' after Test 2, respectively. The horizontal distance between the original pipe position and the slip surface which reached the ground surface was 0.5m, which was less than half that of Test 1.
Figures 8 (a), (b), (c) show the ground surface of the test compartment and the plane of soil slip observed at the Section A-A' after Test 3, respectively. In Test 3, a large crack was created and two slip surfaces were observed. The horizontal distances between the original pipe position and the slip surfaces which reached the ground surface were 0.8m and 2.0m.

Figure 9 shows the experimental results: the normalized force per unit projected area vs. relative displacement of the test pipe in the ground. Here, the 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 three tests are equal using the relationship proposed by Trautmann and O'Rourke [5], and also was normalized with the maximum values recorded in Test 1. The maximum force recorded in Test 2, which used EPS blocks for backfill, was 54% of that of Test 1. The maximum force recorded in Test 3, which used EGW for backfill, was 35% of that of Test 1. From these experimental results, the lateral forces on the pipes with lightweight backfill can be reduced to approximately half of that with normal (the sand) backfill. Quantitative evaluation of the reduction in forces can be achieved by eliminating the effect of loading rods and the edges of the pipe section and by considering other conditions of the ground.



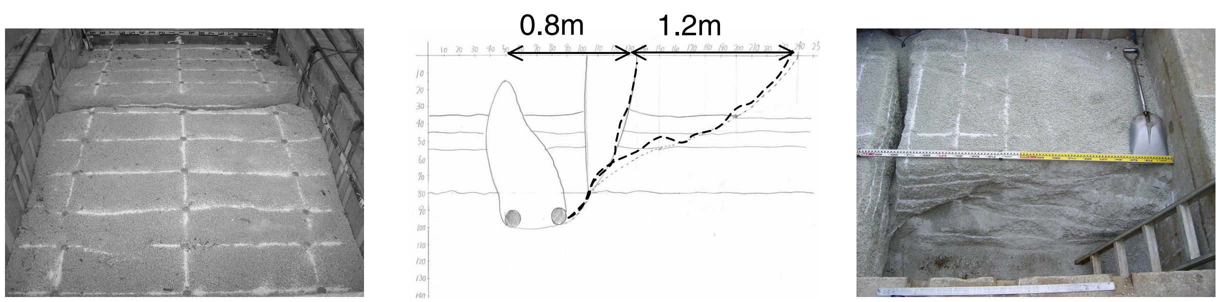
(a) Ground surface (b) Slip surface at Section A-A’ (c) Sketch of ground deformation

Figure 6 Ground deformation after Test 1 (only sand)



(a) Ground surface (b) Slip surface at Section A-A’ (c) Sketch of ground deformation

Figure 7 Ground deformation after Test 2 (EPS)



(a) Ground surface (b) Slip surface at Section A-A’ (c) Sketch of ground deformation

Figure 8 Ground deformation after Test 3 (EGW)

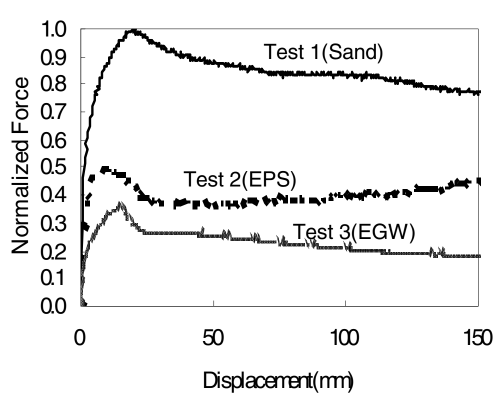


Figure 9 Experimental results

EFFECT OF LIGHTWEIGHT BACKFILL ON DEFORMATION BEHAVIOR OF PIPELINES SUBJECTED TO PGD

Analytical model

Finite element analyses were conducted to investigate the effect of lightweight backfill on enhancement of earthquake-resistance of buried pipelines against PGD using the obtained experimental data. Figure 10 illustrates the assumed phenomenon to evaluate the effect of lightweight backfill. This phenomenon shows a pipeline with an elbow subjected to PGD consistent with lateral spread and/or landslides.

Figure 11 shows the analytical model to simulate such phenomenon. In this model, 400-mm-diameter pipeline (API-5L-X60) is comprised of a 3 DR-90^{o} elbow and 400m length straight pipes on both sides of the elbow. For simulating large-scale pipeline and elbows response to PGD, we used a modeling technique named HYBRID model, using shell elements for the portions where large or localized strains occur and beam elements where a relatively small deformation is expected. The assumed ground displacement is 3m in this study.

Three kinds of analyses, Case 1, Case 2 and Case 3 were conducted. In Case 1, normal sand was used as backfill for all areas. In Case 2 and Case 3, EPS blocks and EGW, respectively, were assumed to be used. In all cases, soil-pipeline interaction in the axial direction of pipelines was modeled in accordance with Japan Gas Association guideline [11]. In Case 2 and 3, soil-pipeline interaction in the lateral direction were modeled with reduction of the peak value of the force using experimental results as shown in Figure 12(b). ABAQUS Version 6.3 was used as a solver for the analyses with geometric nonlinearity and large strain deformation.

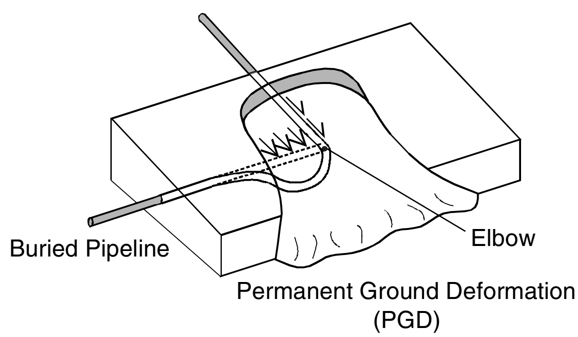


Figure 10 Assumed phenomenon of a buried pipeline with an elbow subjected to PGD

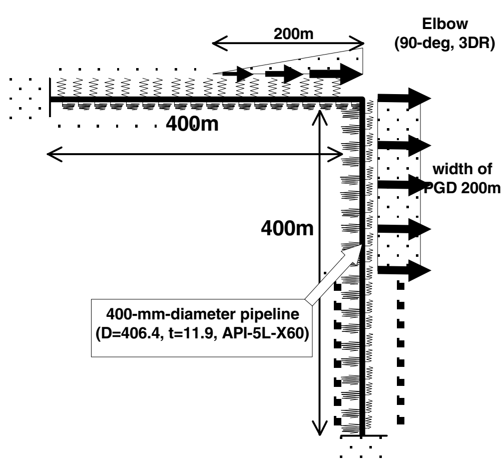
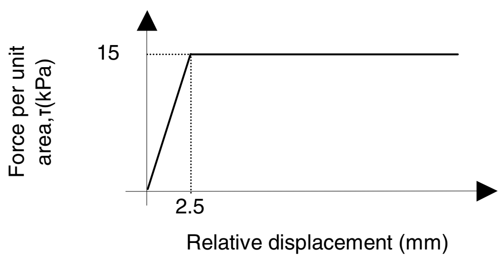
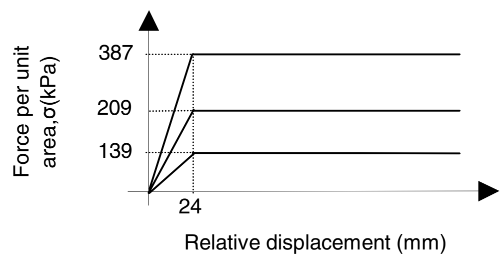


Figure 11 Analytical model



(a) Axial direction



(b) Lateral direction

Figure 12 Soil-pipeline interaction [5, 6, 11]

Analytical results

Figure 13 shows the relationships between ground displacement and maximum strain in either the longitudinal or circumferential direction. The maximum strain in Case 2, which used EPS blocks for backfill, was 58% of that of Case1. The maximum strain in Case 3, which used EGW for backfill, was 47% of that of Case 1 when the ground displacement is 3m. Therefore, lightweight backfill showed significant effect for enhancement of earthquake-resistance of buried pipelines subjected to PGD.

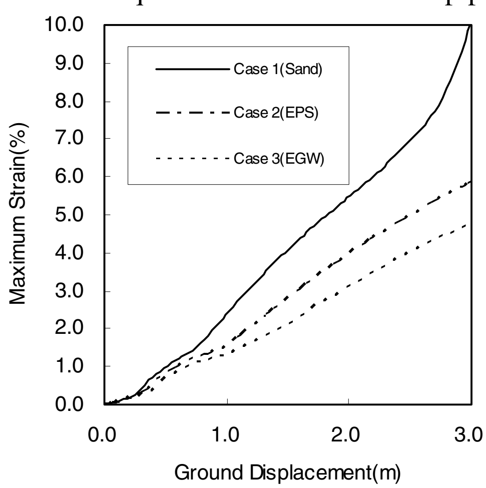


Figure 13 Analytical results

CONCLUSION

In this paper, the effect of lightweight backfill on the reduction of soil-pipeline interaction was investigated by conducting full-scale experiments. When EPS blocks and EGW were used for backfill, the lateral forces on the pipes could be reduced to approximately half that with normal backfill. Experimental results showed that lightweight backfills had 56% and 34% reduction, respectively, on the soil-pipe interaction in the case that the cover-depth is 0.9m.

Furthermore, 400-mm-diamter pipeline with a 90-degree elbow was used to evaluate the effect of lightweight backfill on large deformation behavior subjected to PGD using Finite Element analytical model with the observed reduction in soil-pipe interaction. The results showed that lightweight backfill had 58% and 47% reduction, respectively, on the strain of the pipelines deformation when the ground displacement is 3m. As a result, lightweight backfill had significant effect for enhancement of earthquake-resistance of buried pipeline.

ACKNOWLEDGEMENT

The authors wish to thank Messrs. Kazunori Shimamura, Takahito Watanabe, Naoto Hagiwara and Hiroshi Sugahara of Tokyo Gas Co., Ltd., for the invaluable advice and Messrs. Takehito Suzuki, Yasuyuki Takahashi and Mitsuru Hirayama of Kanpai Co., Ltd., for their assistance in conducting the experiments. Hitoshi Mizutani provided the invaluable advice on EGW. Thanks are extended to Professor Susumu Yasuda of Tokyo Denki University for suggestions, which led to significant improvement in the research.

REFERENCES

1. O'Rourke, T. D. and Lane, P.A. "Liquefaction Hazards and Their Effects on Buried Pipelines," Technical Report, NCEER-89-0007, NCEER, Buffalo, NY, 1989.
2. Hamada, M. "Large Ground Deformations and Their Effects on Lifeline: 1989 Nihonkai-Chubu Earthquake, "Proceedings, Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes Volume 1 Japanese Case Studies, MCEER-92-0001, NCEER, Buffalo, NY, 1992.
3. O'Rourke, T. D. and Palmer, M. C. "Earthquake Performance of Gas Transmission Pipelines," Earthquake Spectra, Vol. 20, No. 3, 1996: 493-527.
4. Oka, S. "Damage of Gas Facilities by Great Hanshin Earthquake and Restoration Process," Proceedings, 6th Japan-U.S. Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction, NCEER-96-0012, MCEER, Buffalo, NY, 1996: 111-124.
5. Trautmann, C.H. and O'Rourke, T.D. "Lateral Force-Displacement Response of Buried Pipes," Journal of Geotechnical Engineering, ASCE, Reston, VA, Vol.111, No.9, 1985: 1077-1092.
6. Trautmann, C.H., O'Rourke T.D and Kulhawy F.H. "Uplift Force-Displacement Response of Buried Pipes," Journal of Geotechnical Engineering, ASCE, Reston, VA, Vol.111, No.9, 1985: 1061-1076.
7. Horvath, J.S. "Applications," Geofoam Geosynthetic, Horvath Engineering P.C., 1995: 79-112.
8. Mizutani, H., Kato, Y., Abe, H. and Fukuzawa, E., "Properties of Expanded Glass Wastes as Lightweight Ground Material and Application Result to Back Filling," Proceedings, Symposium of Development and Application on Lightweight Geo-Materials, Kyoto, Japan, 2000.
9. Bureau of Construction of Tokyo Metropolitan Government. Specification for Civil Material, Bureau of Construction of Tokyo Metropolitan Government (in Japanese), Tokyo, Japan, 1999.
10. Yoshizaki, K., O'Rourke, T.D. and Hamada, M. "Large Deformation Behavior of Buried Pipelines with Low-angle Elbows Subjected to Permanent Ground Deformation," Journal of Structural Mechanics and Earthquake Engineering, Vol. 18, No. 1, No. 675/I-55, 2002: 41-52.
11. Japan Gas Association. "Recommended Practice for Earthquake Resistant Design of High Pressure Gas Pipelines", Japan Gas Association (in Japanese), Tokyo, Japan, 2000.
12. Yoshizaki, K. and Oguchi, N. "Estimation of the deformation behavior of elbows for an earthquake-resistant design," Proceedings, 11th World Conference on Earthquake Engineerings, Acapulco, Mexico, Paper No. 1783, Elsevier Science, 1996.
13. Sakanoue, T. and Yoshizaki, K. "Experimental Study on the Effect of Lightweight Backfill for Enhancement of Earthquake Resistance of Buried Pipelines," Proceedings, 22ND International Conference on Offshore Mechanics and Arctic Engineering, 2003.