LOAD ON PIPES BURIED IN A NON-LIQUEFACTION LAYER DUE TO LIQUEFACTION-INDUCED GROUND DISPLACEMENT

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SUMMARY

Using a dynamic centrifuge model test, this study investigated the transverse horizontal and the axial load acting on pipes due to liquefaction-induced ground displacement.

In order to confirm that the centrifuge model test could be adopted in this study, the pipe was forcibly moved in the transverse horizontal and the axial direction, respectively, in a 30 g centrifuge acceleration field. The measured load showed a good agreement to that found in a 1 g field from the literature.

The load on the pipes due to liquefaction-induced ground displacement was measured using the quaywall model experiment. The pipe was buried in the ground at the back of the quaywall. By shaking the model apparatus, horizontal ground displacement was induced in the ground, and the load on the pipe due to this displacement was measured. It is important to note that the pipe was always buried in the non-liquefaction layer above the liquefaction layer.

The centrifuge acceleration was 50 g and 30 g. The prototype pipe was 60 cm – 65 cm in diameter. The pipe was buried at a depth of 180 cm measured from the top of the pipe.

The results were as follows,

1) The maximum transverse horizontal load on the pipe was 0.08 Mpa - 0.11 Mpa (0.8 kgf/cm2 – 1.1 kgf/cm2), which was 1/3 – 1/4 larger than that obtained in the experiments designed to forcibly move the pipe in the ground.

2) The maximum axial shear stress on the pipe was 0.010 Mpa – 0.015 Mpa (0.10 kgf/cm2 – 0.15 kgf/cm2). The experiment method did not make much difference to the axial load.

INTRODUCTION

This study investigated the transverse horizontal and the axial load acting on pipes due to liquefaction-induced ground displacement using a dynamic centrifuge model test, and it is a part of studies undertaken to establish a recommended seismic design practice for buried gas pipelines.

Knowledge of the load acting on buried pipes due to ground displacement is crucial for seismic design. Therefore, many researchers have studied the load-displacement response of buried pipes during earthquakes. There is, however, no report of a study in which liquefaction-induced ground displacement was directly modeled in an experiment.

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Audibert and Nyman[1977] proposed a load-displacement relationship for the transverse horizontal direction by reviewing literature and performing laboratory and in-situ experiments. Trautmann and O'Rourke[1985] also proposed a load-displacement relationship by performing a series of laboratory experiments. In these experiments, however, the pipe was forcibly moved in the ground.

As for the axial direction, Kobayashi et al.[1998] investigated the effect of velocity and cyclic displacement on the axial load. Shimamura et al.[1999] also investigated the axial load by a real scale experiment. These investigations, however, concentrated on the seismic design against wave propagation, in which the ground displacement was cyclic and the amount of displacement was not large.

In this study, the load acting on pipes in the transverse horizontal and the axial directions was investigated using the quaywall model experiment. The pipe was buried in the ground at the back of the quaywall where liquefaction-induced ground displacement occurred when the model apparatus was shaken.

The experiments were performed by using a dynamic centrifuge at the Institute of Technology, Shimizu Corporation. The centrifuge has a maximum payload of 300 kg in a 50 g centrifuge acceleration field for dynamic tests. It is equipped with a shaking table driven by an electro-magnetic shaker. Specifications of the centrifuge and shaking table have been described by Sato[1994 & 1995].

It is important to note that the pipe was always buried in the non-liquefaction layer above the liquefaction layer. This was because the load on pipes in the non-liquefaction layer was considered to be larger than that in the liquefaction layer.

2. PRELIMINARY EXPERIMENTS

In order to confirm that the centrifuge model test could be adopted in this investigation, the pipe was forcibly moved in the transverse horizontal and the axial direction in the ground in a 30 g centrifuge acceleration field.

Fig. 1 and Fig. 2 show the plan view of the forced pipe displacement model for the transverse horizontal and the axial load experiments, respectively. The model ground was made in a rigid container using silica sand No.8 with the optimum water content. The relative density of the model ground was about 100%. Fig. 3 shows the grading curve and the physical properties of silica sand No.8. A pipe 2 cm in diameter was buried at a depth of 6 cm measured from the top of the pipe. As the centrifuge acceleration was 30 g, the pipe was 60 cm in diameter and it was buried at a depth of 180 cm in the prototype.

Fig. 4 shows an example of the load-displacement relationship in the transverse horizontal load experiment. Two experiments were conducted in the same conditions. Table 1 summarizes the results. Both experiments showed similar results. As the relative density of the model ground was about 100%, the internal friction angle may be assumed to be about 45^{o}. Using this internal friction angle, the figure proposed by Trautmann and O'Rourke[1985] based on the forced pipe displacement experiments in a 1 g field, yielded 0.45 Mpa as the

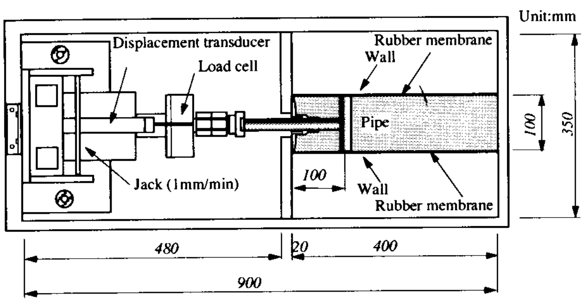


Fig. 1: Plan view of the forced pipe displacement model for the transverse horizontal load

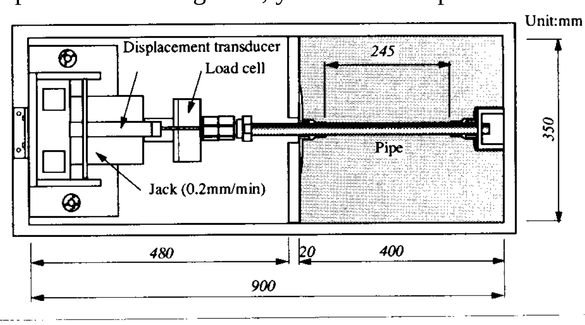


Fig. 2: Plan view of the forced pipe displacement model for the axial load

maximum load in the transverse horizontal direction. The results of the centrifuge model test agreed well with those in a 1 g field.

Fig. 5 shows an example of the load-displacement relationship in the axial load experiment. Two experiments were conducted under the same conditions. Table 2 summarizes the results. Both experiments showed similar results. The maximum shear stress acting on the pipe surface has been studied in a real scale experiment in a 1 g field by Shimamura et al.[1999]. It was 0.011 Mpa – 0.015 Mpa in case of low-rate forced pipe displacement experiments. Although the centrifuge model test showed higher results, the difference was considered to be within the accepted range.

From these preliminary experiments, it was concluded that the centrifuge model test was reliable as a tool for investigating the load acting on buried pipes.

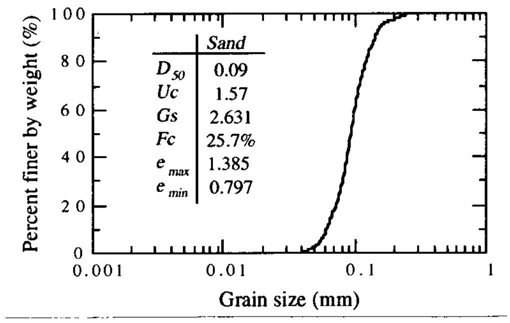


Fig. 3: Grading curve and physical properties

Table 1: Maximum load per unit area[1)] in the transverse horizontal load experiment

Unit: Mpa

Case 1	Case 2
0.46	0.47

1) Maximum force / projected area of the pipe(diameter x length)

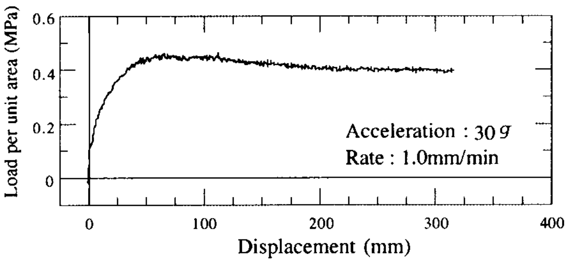


Fig. 4: Load-displacement relationship in the transverse horizontal load experiment

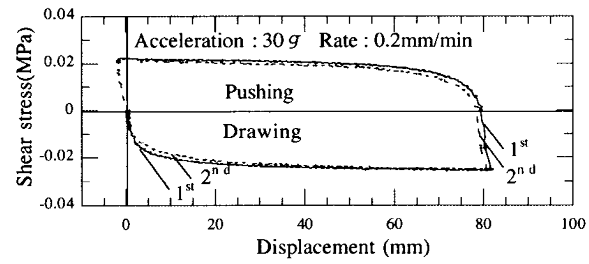


Fig. 5: Load-displacement relationship in the axial load experiment

Table 2: Maximum shear stress[1)] in the axial load experiment

Unit: Mpa

Cycle	Case 1	Case 2
1st cycle - Drawing	0.025	0.019
1st cycle - Pushing	0.022	0.020
2nd cycle - Drawing	0.025	0.020
2nd cycle - Pushing	0.021	0.021
Average	0.023	0.020

1) Maximum load / surface area of the pipe in the ground

3. LIQUEFACTION-INDUCED GROUND DISPLACEMENT MODEL EXPERIMENTS

3.1 Transverse Horizontal Load

3.1.1 Experiment conditions

Fig. 6 shows the liquefaction-induced ground displacement model for the transverse horizontal load experiments. Table 3 shows the experiment conditions. The model was made in a laminar container by scattering silica sand No. 8. The ground comprised two layers. The lower was the liquefaction layer whose relative density was about 40%, and the upper was the non-liquefaction layer whose relative density was about 70%. The boundary was at

30 cm – 50 cm below the pipe. The model pipe was buried in the non-liquefaction layer. And its edges were fixed to prevent horizontal displacement. The boundary condition was the same as that for a simply supported beam. Strain gauges were placed on the inside wall of the pipe. To saturate the liquefaction layer, the laminar container was put in a vacuum box and silicon oil was poured from the bottom of the container.

3.1.2 Example of measured acceleration, pore water pressure and ground displacement

Fig. 7 and Fig. 8 show the time histories of acceleration and pore water pressure in experiment T1 in the proto-

Table 3: Experiment conditions for the transverse horizontal load

Experiment No.	Centrifuge acceleration(g)	Pipe diameter (cm)[1)]	Pipe-quaywall Distance(m) [1)]	Ground water level(m) [1)]	Input acceleration(gal) [1)]
T1	50	65	7.5	GL-4.6	250
T2	50	65	7.5	GL-4.0	300
T3	50	65	7.5	GL-3.0	150
T4	50	65	7.5	GL-4.2	140
T5	30	60	3.0	GL-2.7	330
T6	30	60	3.0	GL-2.7	330

1) Prototype scale.

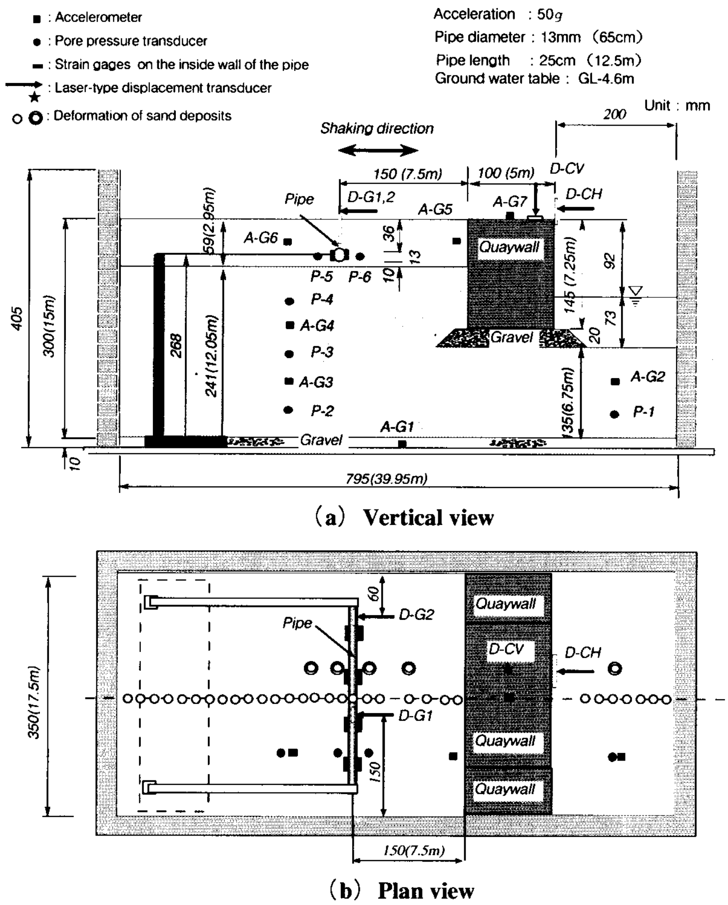


Fig. 6: Liquefaction-induced ground displacement model for the transverse horizontal load

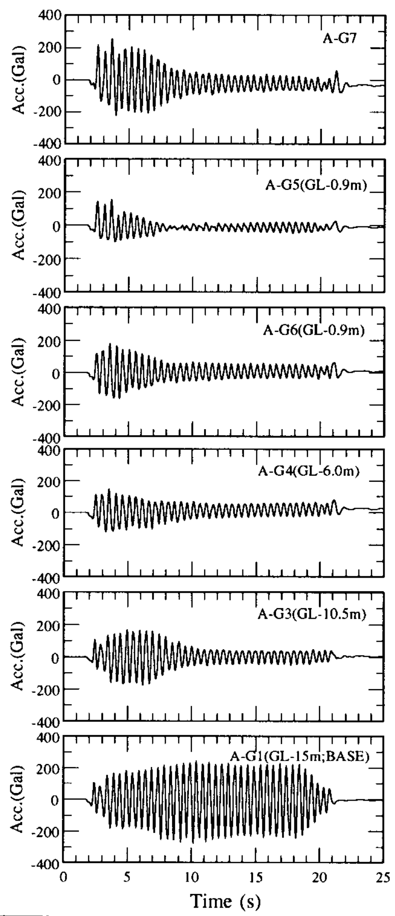
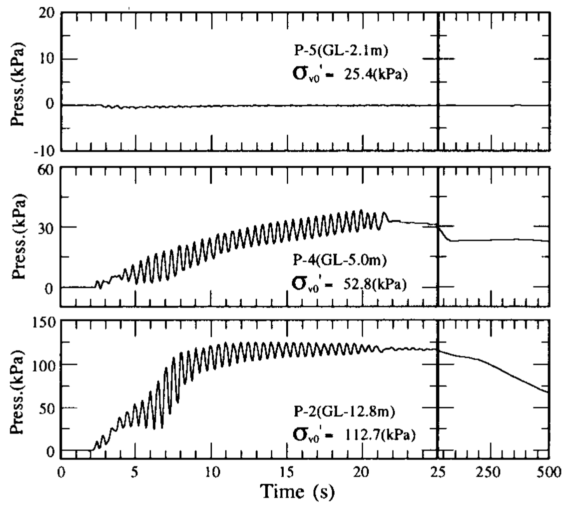


Fig. 7: Time histories of acceleration in experiment T1



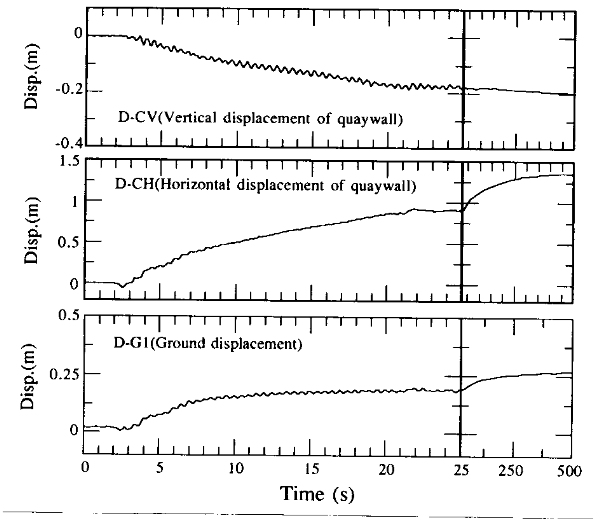


Fig. 8: Time histories of pore water pressure in experiment T1

Fig. 9: Time histories of quaywall and ground surface displacement in experiment T1

type scale. These time histories indicate that the ground below the ground water level liquefied completely. It should be noted from Fig. 8 that the pore water pressure at GL-2.1 m did not increase. This means that the pore water pressure did not affect the load on the pipe.

Fig. 9 shows the time histories of displacement of the quaywall and the ground surface just above the pipe in experiment T1. The quaywall moved horizontally by about 1.3 m in total. The ground surface moved by about 0.3 m in total. In other experiments, the horizontal movement of the quay wall was 1.0 m – 2.3m, and the ground surface movement just above the pipe was 0.2 m – 0.6 m. Fig. 10 and Fig. 11 show the sketch and the ground displacement at the cross section after experiment T1. The ground displacement was measured by tracing the movement of bead targets. It was found from Fig. 11 that the horizontal displacement of the ground on rear side of the pipe was restrained by the pipe. The ground on the quaywall side of the pipe moved horizontally with the movement of the liquefaction layer. Therefore, the ground in front of the pipe collapsed as is shown in Fig. 10.

3.1.3 The load –displacement relationship and discussions

Fig. 12 show the time histories of bending strain on the pipe in experiment T1. Assuming that uniformly distributed load acted on the pipe, the magnitude of this load can be estimated by measuring the bending strain. Fig. 13 shows the measured and the estimated bending moment at 25 sec in experiment T1. The estimated bending moment was obtained using the estimated uniformly distributed load. The assumption of uniformly distributed load is justified from Fig. 13.

The relationship between the estimated uniformly distributed load and the ground surface displacement just above the pipe in six experiments is shown in Fig. 14. The maximum load per unit area was 0.08 Mpa – 0.11 Mpa. Neither the ground water level nor the centrifuge acceleration showed much effect on the magnitude of the maximum load.

The relative density of the non-liquefaction layer was about 70% and therefore, the internal friction angle may be assumed to be about 40^{o}. Using this internal friction angle, Trautmann and O'Rourke[1985] yielded 0.34 Mpa as a maximum transverse horizontal load. In this study, the measured maximum horizontal load was 1/3 – 1/4 larger than that proposed by Trautmann and O'Rourke. In the experiments, the pore water pressure did not increase around the pipe. Therefore, the decrease in the load was not caused by the increase of pore water pressure. In this study, liquefaction-induced ground displacement was directly modeled. However, the load proposed by Trautmann and O'Rourke was based on experiments in which the pipe was forcibly moved in the ground and no liquefaction layer was present. This difference in the experiment method may have caused the difference in the maximum load in the transverse horizontal direction.

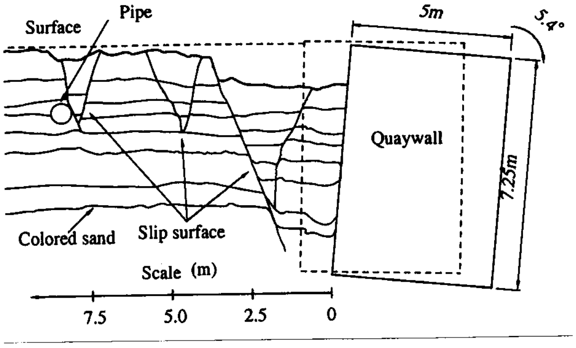


Fig. 10: Sketch at the cross section after experiment T1

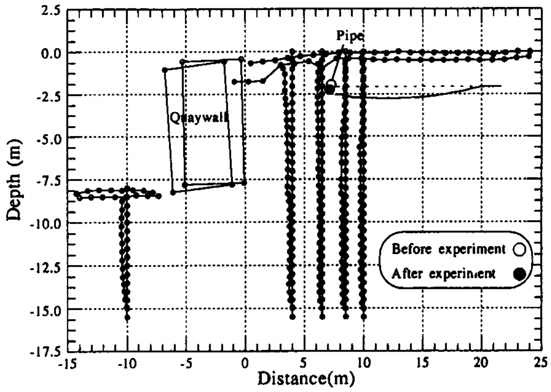


Fig. 11: Ground displacement at the cross section after experiment T1

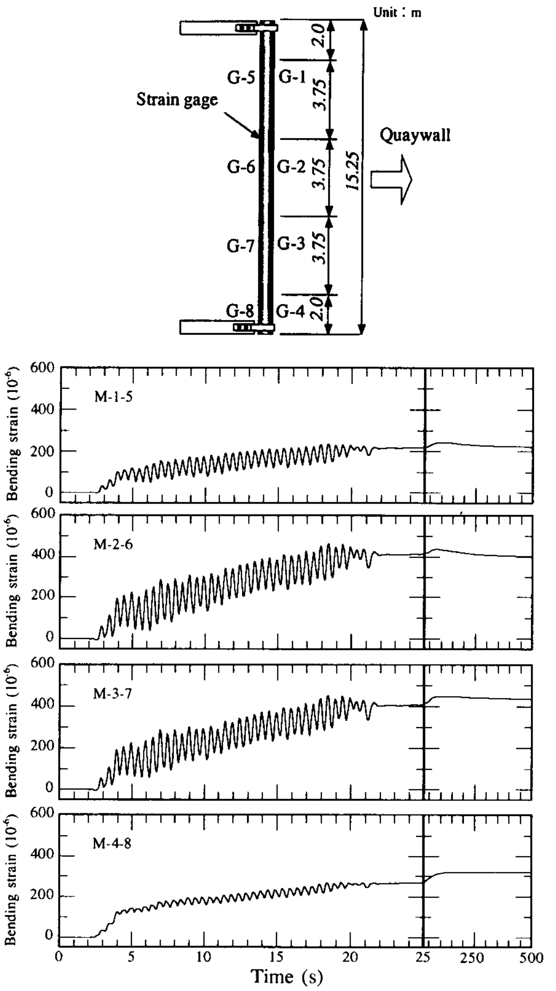


Fig. 12: Time histories of bending strain on the pipe in experiment T1

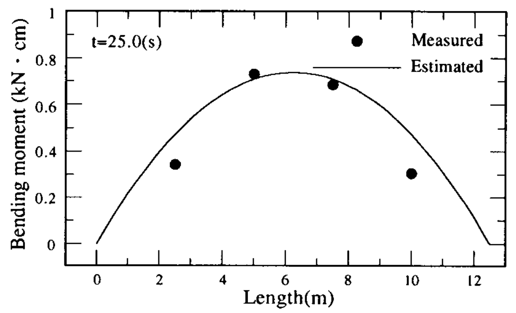
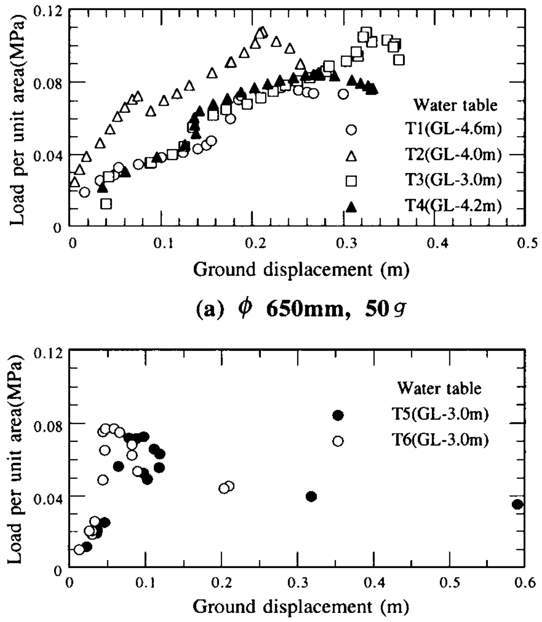


Fig. 13: Measured and estimated bending moment along pipe axis in experiment T1



(a) ϕ 650mm, 50g

(b) ϕ 600mm, 30g

Fig.14: Load-displacement relationship in the transverse horizontal load experiment

3.2 Axial Load

3.2.1 Experiment conditions

Fig. 15 shows the liquefaction-induced ground displacement model for the axial load experiments. Table 4 shows the experiment conditions. The model was made in the same way as that used in the transverse horizontal load experiments.

3.2.2 The shear stress-displacement relationship and considerations

Fig. 16 shows the time history of axial strain in experiment A4, in which the vibration component was removed. At the start of the experiment, the axial strain was not zero because the ground had moved a little during the stage of increasing the centrifuge acceleration. Assuming that uniformly distributed shear stress acted on the pipe surface, the magnitude of this stress can be estimated. Fig. 17 shows the axial strain distribution along the pipe axis at 5 sec in experiment A4. Using three axial strain data from the edge of the pipe, the uniformly distributed shear stress was estimated.

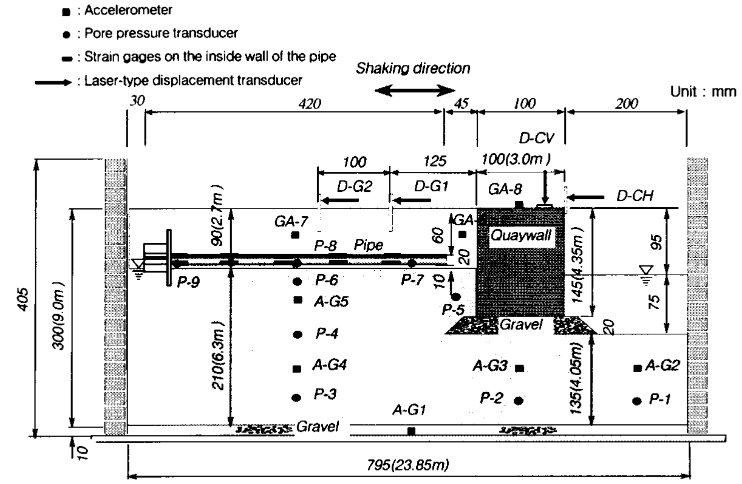


Fig. 15: Liquefaction-induced ground displacement model for the axial load

Table 4: Experiment conditions for the axial load

Exp. No.	Pipe diameter (cm)[1)]	Pipe-quaywall Distance(m)[1)]
A1	60	1.5
A2	60	3.0
A3	60	1.5
A4	60	1.5
A5	40	3.0
A6	40	1.5

1) Prototype scale.
* Centrifuge acceleration: 30 g,
Ground water table: GL-2.7 m,
Input acceleration: 330 gal.

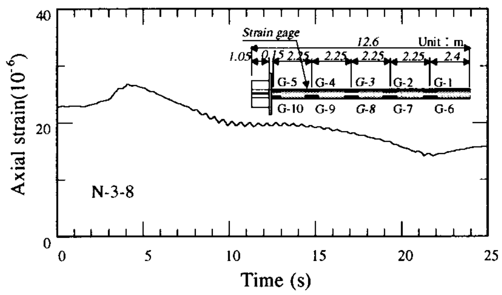


Fig.16: Time history of axial strain in experiment A4

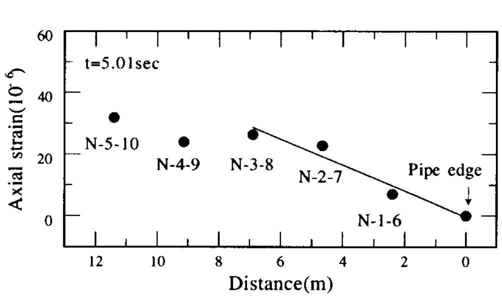


Fig. 17: Axial strain distribution in experiment A4

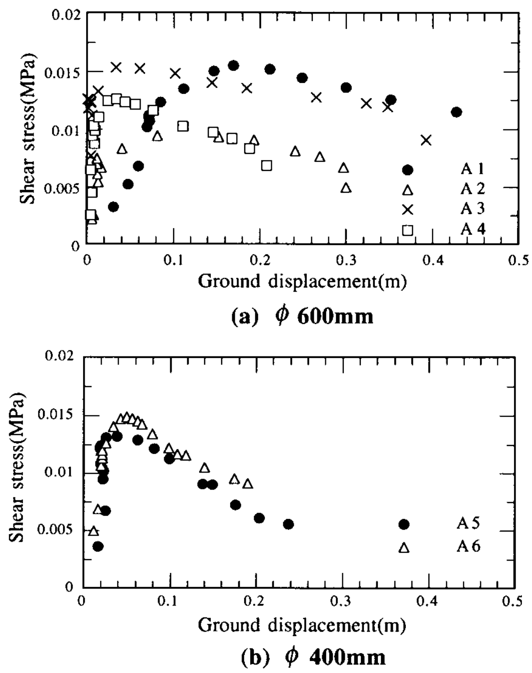


Fig. 18: Load-displacement relationship in the axial load experiment

The relationship between the estimated shear stress and the ground surface displacement at 3.75 m apart from the quaywall in six experiments is shown in Fig. 18. The maximum shear stress was 0.010 Mpa – 0.015 Mpa.

As mentioned in chapter 2, the load measured in the forced pipe displacement model by preliminary centrifuge experiments was 0.020 Mpa – 0.023 Mpa. The load in the same model by real scale experiments reported by Shimamura et al.[1999] was 0.010 – 0.015 Mpa. As the difference in the relative density of the ground must be considered, 0.010 Mpa – 0.015 Mpa, the results obtained in the liquefaction-induced ground displacement model, seem to be roughly the same as, or a little less than, the load obtained in the forced pipe displacement model. This means that the experiment method did not make much difference to the axial load.

4. CONCLUSIONS

The transverse horizontal and the axial load acting on pipes due to liquefaction-induced ground displacement was investigated using a dynamic centrifuge model test. The pipe was buried in the non-liquefaction layer above the liquefaction layer. The conclusions are as follows.

(1) The measured load in the centrifuge model test in which the pipe was forcibly moved in the ground showed a good agreement to that obtained in the 1 g field. The centrifuge model test was confirmed to be reliable as a tool for investigating the load acting on pipes.

(2) The maximum transverse horizontal load per unit area was 0.08 Mpa – 0.11 Mpa in the liquefaction-induced ground displacement model experiments in which the pipe was buried in the ground at the back of the quaywall. The load was 1/3 – 1/4 larger than that obtained in the experiments in which the pipe was forcibly moved in the ground. The difference in the experiment method may have caused the difference in the maximum transverse horizontal load.

(3) The maximum axial shear stress was 0.010 Mpa – 0.015 Mpa in the same experiment as mentioned in (2). The experiment method did not make much difference to the axial load.

ACKNOWLEDGMENTS

After the 1995 Hyogoken Nanbu Earthquake, the Agency of Natural Resources and Energy, Ministry of International Trade and Industry entrusted the investigation of gas pipe behavior due to liquefaction to the Japan Gas Association. This investigation started in 1996 and will take five years to complete. It is supervised by the committee for investigation of the effect of liquefaction on gas pipelines, chaired by Dr. Tsuneo Katayama, the head of the National Research Institute for Earth Science and Disaster Prevention of the Science and Technology Agency. The authors express their gratitude to all persons concerned at MITI for their permission to publish this paper, and the committee members for their valuable suggestions.

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