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AN EXPERIMENTAL STUDY ON THE ANTI-SEISMIC PERFORMANCE OF A U-PVC WATER SUPPLY PIPELINE WITH ENLARGED EXPANSION JOINTS

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ABSTRACT

This paper reports on a full-scale experiment and numerical analysis performed to verify the earthquake resistance of a rubber ring (RR)-type U-PVC pipeline with enlarged expansion joints for water distribution. In the experiment, one end of a buried model pipeline measuring 20 m in length was pulled out and/or pushed in using a hydraulic jack to simulate the relative ground movement that occurs during the sliding of a soil mass parallel to the pipeline's longitudinal axis. The results indicated a high level of expansion performance and slip-out prevention capability in the expansion joints. Furthermore, a high-speed loading experiment for the expansion joints was carried out to verify their performance against seismic relative ground movement. The outcome clarified that the enlarged expansion joints with slip-out prevention offer a high level of anti-seismic performance for U-PVC water supply pipelines.

Keywords: Anti-seismic performance; expansion joint; U-PVC pipeline

1. INTRODUCTION

In the past, serious pipeline damage has been caused by seismic relative ground movement (fissures) as well as permanent ground displacement (PGD) induced by liquefaction. As a result, after the 1995 Hyogo-ken Nambu Earthquake, PGD in liquefiable ground was taken into consideration in the revised anti-seismic design guidelines for water supply pipelines in Japan [1]. An earthquake's effect on pipelines is treated as permanent ground strain (PGS), which is represented by the average value of tensile or compressive strain over a 100-m length of ground surface along a pipeline.

However, it has been observed that both the locations and widths of fissures in the ground surface show a close correlation to pipeline damage. It is also clear that the ground surface cannot remain continuous when the relevant tensile strain exceeds its elastic level. Accordingly,

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the authors have studied the relationship between PGS and fissure width by analyzing PGD data observed in Noshiro City after the 1983 Nihonkai-Chubu Earthquake.

A new expansion joint for RR U-PVC water supply pipelines was designed to withstand a 1.5% permanent ground strain as well as a 20 cm fissure. As shown in Figure 1, it is composed of a slip-out prevention device and an enlarged pipe end with an expansion capability of ±75 mm, into which a spigot pipe end fits. When the relative ground movement is assumed to be that of the ground-block model illustrated in Figure 2, a 20-cm fissure must be absorbed by the expansion of three joints. The slip-out prevention strength F of the joint that lies at the fissure must therefore be higher than the total soil friction force acting on one pipe in order to propagate the axial force to the neighboring joints on the right and left.

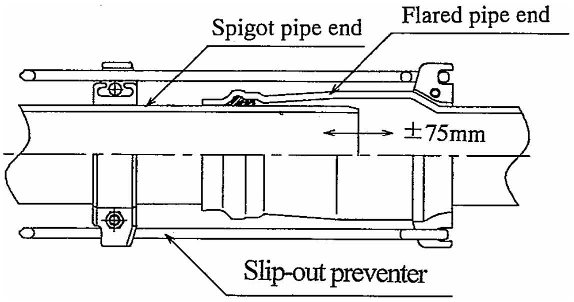


Figure 1. Joint structure of new RR U-PVC pipe

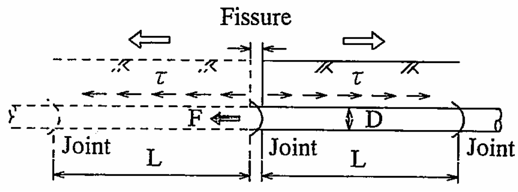


Figure 2. Ground block model

2. PIPELINE DAMAGE RELATED TO FISSURES DURING PAST EARTHQUAKES

According to investigations of buried pipelines damaged during past earthquakes in Japan, the points at which damage occurs are closely related to both the locations and widths of fissures in the ground surface.

The Japan Ductile Iron Pipe Association conducted an investigation on joint movement in ductile cast-iron pipelines in the Kobe area after the 1995 Hyogo-ken Nambu Earthquake[2]. Both the amount and the location of joint movement measured using a TV camera inserted into the pipelines were shown to be closely in line with the widths and locations of fissures that had appeared in the ground surface.

Photo 1 shows an example of damaged PVC water distribution pipelines in Kitahiyama Town during the 1993 Hokkaido-Nansei-Oki Earthquake [3]. PVC pipelines with rubber-ring-type joints were damaged at 31 locations, with most of the damage caused by the slip-out of joints as shown in Photo 1. The waterworks division of Kitahiyama Town reported that many fissures were found in the ground surface around the damaged pipeline locations, as shown in Photo 2. The same situation was also found in Hokudan Town on Awaji Island where the epicenter of the 1995 Hyogo-ken Nanbu Earthquake was situated. In this area, PGD due to the collapse of steep slopes occurred along small roads under which water distribution pipelines ran. In most cases, damage involving the slip-out of joints was related to fissures and uneven ground subsidence in the road surface [4].

Photo 1. RR joint slip-out

Photo 2 A fissure in the ground surface

3. EXPERIMENT TO CONFIRM THE PERFORMANCE OF U-PVC PIPELINE WITH EXPANSION JOINTS

Figure 3 shows an outline of the experiment. A model pipeline measuring 20 m in length with three new RR joints was buried in a test field. The nominal diameter of the pipe was 100 mm, and the design strength of the slip-out preventer was more than 35 kN. One end of the pipeline was connected to a hydraulic jack. By pulling out and/or pushing in the pipe end, relative ground movement considered to correspond to the pipeline damage found in Kitahiyama and Hokudan towns (such as fissures and/or compression – the opposite of fissures) was simulated along the stretch of pipeline. The longitudinal displacement of the pipe was measured using wire-type displacement transducers connected to the flared pipe end and the spigot pipe end at each joint. Longitudinal force was applied to the pipeline in stages with the estimated maximum force divided into about 30 steps, and the resulting behavior was measured at each stage. The in-situ dry density of the model ground was about 93% to 96% of the maximum dry density.

The analytical model using beam theory is shown in Figure 4. The non-linear characteristics of the soil spring and joint expansion were taken into consideration.

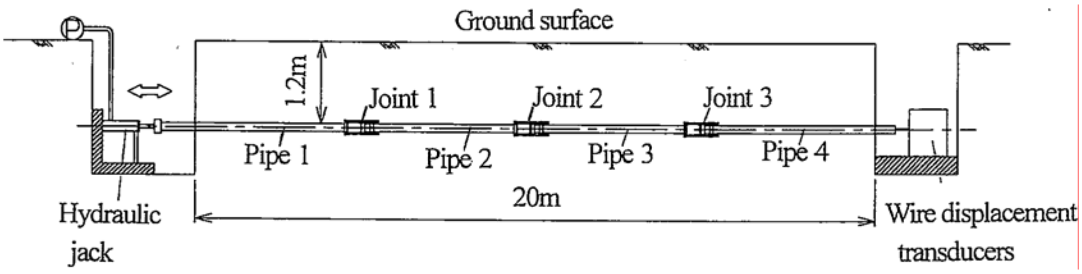
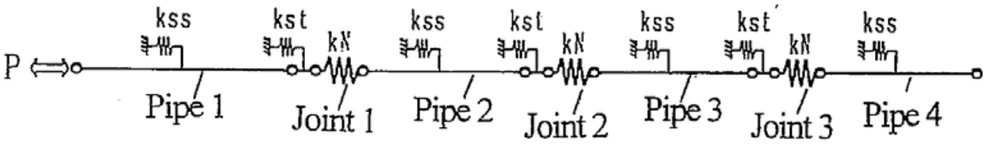


Figure 3. Experimental method



kss: Ground spring for pipe
kst: Ground spring for joint
kN: Joint spring (expansion)

Figure 4. Analytical model

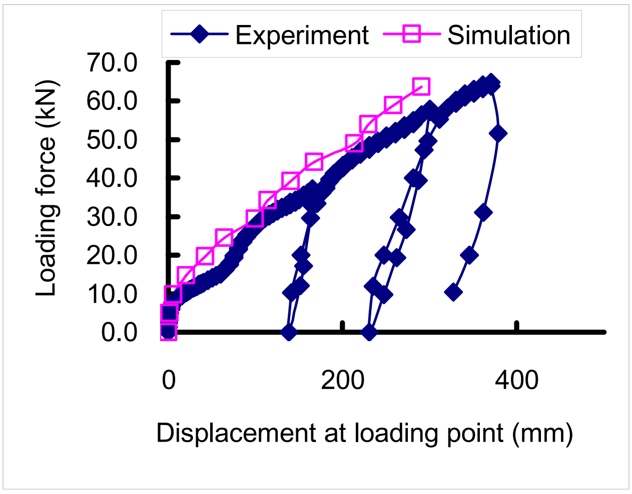


Figure 5. Force-displacement relationship (pulling out)

Figure 5 shows the force-displacement relationship at the loading point. The maximum force was 64.7 kN, and the pull-out displacement at that time was 370 mm. Joint 1 subsequently slipped out, and the experiment was stopped. The rapid reduction in force was due to the resetting of the jack system. Small jumps in the force appeared three times when each joint started to move due to higher ground resistance. The analytical results of the force-displacement relationship agreed with those of the experiment fairly accurately.

The relationship between the loading force and expansion of each joint is shown in Figure 6. The slip-out displacement of each joint was held to within 75 mm, which proved the efficacy of the slip-out prevention measures. Although the design strength of the prevention device was more than 35kN, the maximum resistant force was estimated at more than 44kN. In the experiment, the prevention of joint slippage was achieved after the joint moved about 60mm, while the same prevention effect appeared at 75mm in the analysis.

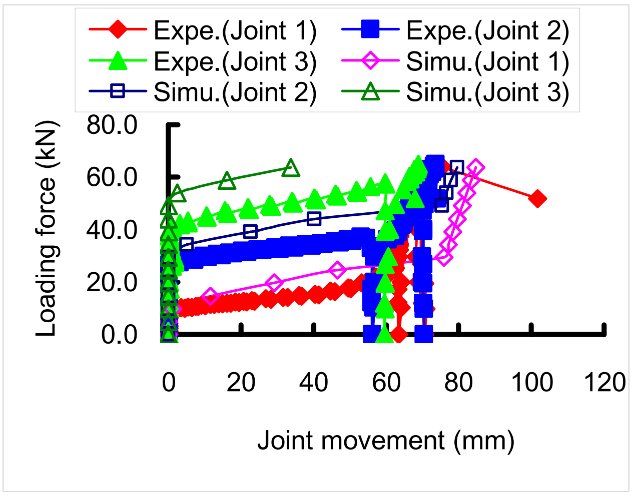


Figure 6. Joint expansion (pulling out)

Figure 7 shows the force-displacement relationship at the loading point. The maximum force was 65.7kN, and the push-in displacement at that time was 400 mm. All pipes subsequently started to move and the force did not increase, so the experiment was stopped. The loading jack system was reset three times. The analytical results of the force-displacement relationship agreed with those of the experiment fairly accurately.

The relationship between the loading force and the expansion of each joint is shown in Figure 8. The retraction displacement of each joint was held to within 75 mm, which proved the efficacy of the slip-out prevention measures. The joints were observed in detail after excavation, but no slippage of the prevention mechanism was found. In general, the analytical data showed good agreement with the experimental data.

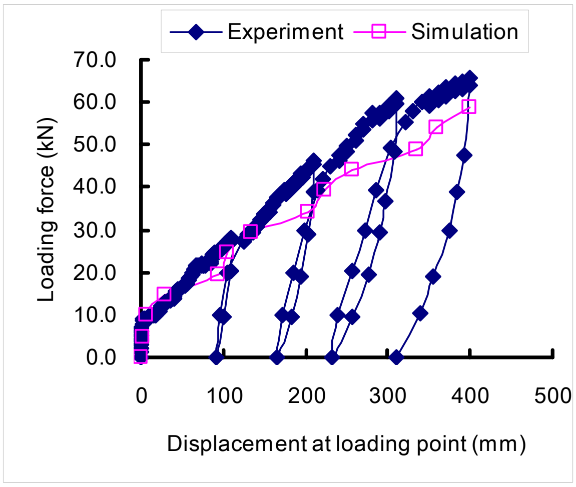


Figure 7. Force-displacement relationship (pushing in)

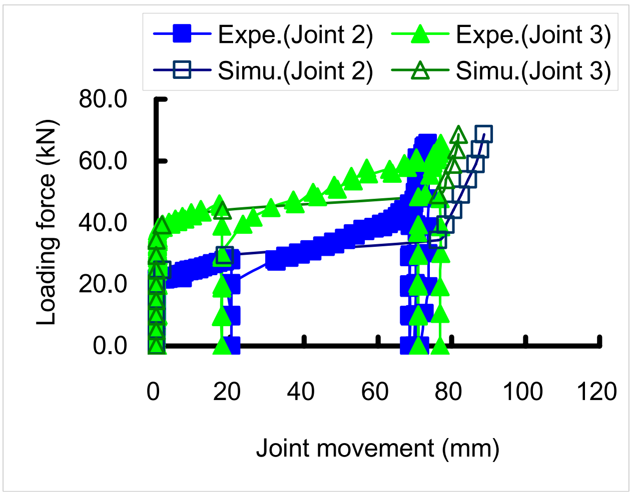


Figure 8. Joint expansion behavior (pushing in)

4. HIGH-SPEED LOADING EXPERIMENT FOR THE EXPANSION JOINT WITH SLIP-OUT PREVENTION

The experiment described above was a static-loading-type test. Therefore, the authors subsequently carried out a high-speed loading experiment for the expansion joint with slip-out prevention to verify its performance against seismic relative ground movement. Figure 9 shows the experimental method. One end of a model pipe segment with an expansion joint was fixed to the reaction wall, and the other end was pulled out and pushed in using a hydraulic actuator at a velocity of 1,000mm/s.

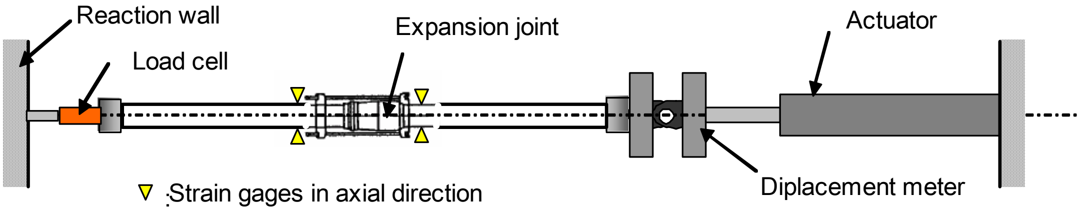


Figure 9. High-speed loading experiment

As shown in Figures 10 and 12, the strength of the slip-out prevention measured in the experiment exceeded its design value both for the pulling and pushing directions even at a velocity of 1,000 mm/s. Until reaching a displacement of ±75 mm, the resistant force of the joint was very small, after which a high level of prevention was seen. The slip-out prevention device finally slipped after the applied load exceeded the design value, but the axial pipe strain observed was under the allowable limit of the U-PVC pipe (10,000×10^{-6}) as shown in Figures 11 and 13. It can therefore be said that a prevention device made of ductile iron will not affect the U-PVC pipe body even under conditions of very-high-speed relative ground movement during an earthquake.

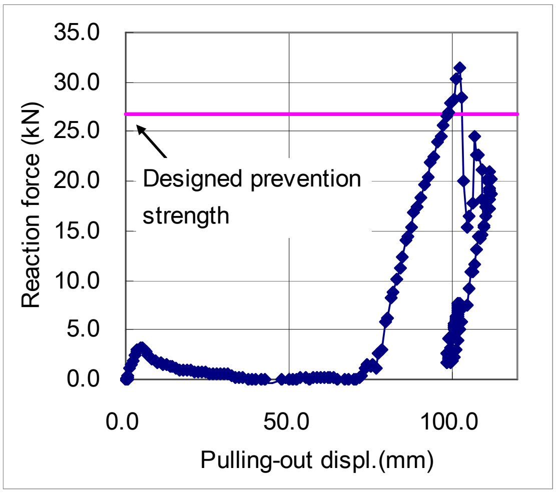


Figure 10. Force displacement (pulling out)

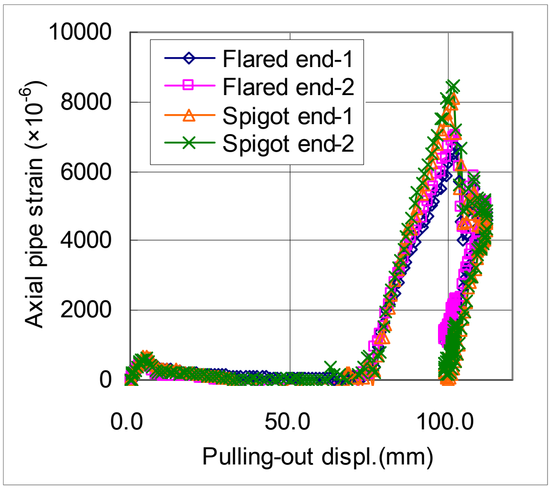


Figure 11. Axial pipe strain (pulling out)

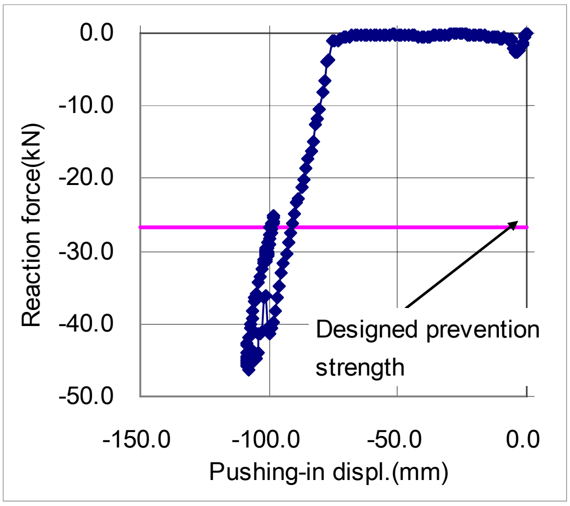


Figure 12. Force displacement (pulling out)

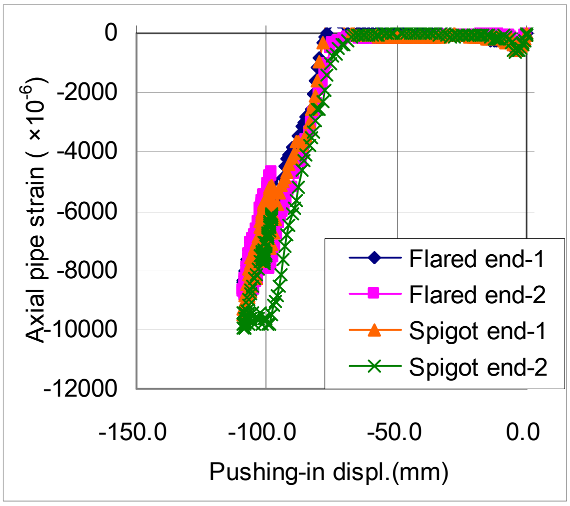


Figure 13. Axial pipe strain (pulling out)

5. RELATIVE-GROUND-MOVEMENT ABSORPTION CAPABILITY OF A PIPELINE

When the relative ground movement is assumed to be that of the ground block model illustrated in Figure 14, the maximum relative displacement (fissure width) δ_p, which is required to break the pipeline, can be given as follows:

$$\delta_p = \frac{E \cdot A \cdot \varepsilon_p^2}{\pi \cdot D \cdot \tau} \tag{1}$$

where E: Young's modulus of the pipe, A: cross-sectional area of the pipe, ε_p: critical strain of the pipe (joint strength), D: outer diameter of the pipe, and τ: soil friction force per unit area of pipe surface.

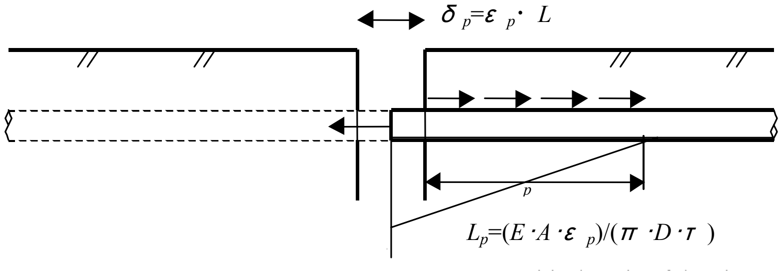


Figure 14. Ground block model

A pipeline with a large δ_p value offers a higher level of resistance against fissures. On the other hand, length L_p, which is the minimum length of the ground block required to break the pipeline, is also considered to play an important role in minimizing pipeline damage. When a pipeline fails in one portion due to a fissure, other fissures that form within distance L_p from the first fissure cannot cause further damage because the length of the ground block becomes less than L_p, and the block cannot provide sufficient force to break the pipeline. Accordingly, the longer L_p becomes, the smaller the possibility of pipeline failure is. Nishio introduced this idea into pipeline damage estimation [5].

The anti-seismic type of ductile cast-iron pipeline, which did not fail in recent earthquakes, is considered to offer excellent earthquake-proof performance because the anti-seismic type of joint provides very high strength, thus preventing it from slipping out under the influence of large ground deformation after reaching its expansion limit. However, such high joint strength has not been taken into account in the anti-seismic design of buried pipelines that have to deal with ground strain.

Table 1 shows the most commonly utilized pipes and joints for water supply pipelines and the values of δ_p and L_p obtained from them. The U-PVC pipeline with the expansion joint reported in this paper is also considered to offer a reasonably high level of performance against relative ground movement.

Table 1. Relative-ground-displacement absorption capability of typical pipeline types

No.	**Application**	**Pipe material**	**Joint type**	**Diameter (mm)**	δ_p **(cm)**	L_p **(m)**
1	Water distribution	Ductile iron	Rubber ring type (K type)	φ300	4.5	5.0
2		Ductile iron	Anti-seismic type (S type)	φ300	200.0	100.0
3		PVC	Expansion joint with slip-out prevention	φ100	20.0	10.0

6. CONCLUSIONS

Through experimentation and numerical analysis, the behavior of an expansion joint for RR U-PVC pipeline subjected to longitudinal ground movement (such as fissures and compression) was ascertained. It was clarified that the expansion and slip-out prevention capabilities of the new joint worked well under buried conditions. Numerical analysis using beam theory seemed to simulate the experiment fairly well.

The new RR U-PVC pipe with slip-out prevention is considered to provide sufficient earthquake resistance for water distribution pipelines even under the severe conditions of Level-2 seismic ground motion and permanent ground deformation due to liquefaction.

REFERENCES

1. Japan Water Works Association: Seismic Design and Construction Guidelines for Water Supply Facilities, 1997.
2. Japan Ductile Iron Pipe Association: Damage to buried water distribution pipelines and ground deformation from the 1995 Hyogoken-nanbu (Kobe) earthquake, Proceedings of IWSA International Workshop, 1998, pp. 43-48
3. Waterworks Division of Kitahiyama Town: A report on post-earthquake investigation of water distribution pipelines after the 1993 Hokkaido-Nansei-Oki Earthquake, 1993.
4. Waterworks Division of Hokudan Town: A report on post-earthquake investigation of water distribution pipelines in Hokudan Town after the 1995 Hyogoken-Nanbu Earthquake, 1995.
5. Nishio N. Anti-seismic design of buried structures, Proceedings of the Workshop on the Earthquake-proof Performance of Lifelines, The Japanese Geo-technical Society, 1995, pp. 41-75.