

Performance verification of novel low-friction cured-in-place pipe for earthquake-induced ground deformation

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Abstract. A cured-in-place pipe (CIPP) rehabilitation involves the installation of flexible polymeric liners within existing pipes. In contrast to pipe replacement, CIPP offers a cost-effective and environmentally sustainable solution for pipe rehabilitation. In conventional CIPP rehabilitation, lining pipes are glued to existing pipes. Even if the joint that connects existing pipes breaks owing to earthquake-induced ground deformation, the lining pipe can still resist tensile deformation. Therefore, the CIPP rehabilitation pipe is considered as effective in preventing joint pull-out. However, because the lining pipe must resist the tensile force on its own after the joint breaks, the lining pipe undergoes large strain. With this background, a novel low-friction CIPP rehabilitation approach was developed in this study. A friction-reducing layer was inserted between the existing pipes and lining pipes to reduce the strain transmitted from the existing pipe to the lining pipe. The objective of this study was to investigate the seismic performance of the low-friction rehabilitation pipe compared with the conventional glued-type rehabilitation pipe under earthquake-induced ground deformation using finite element analysis. To this end, a bending test and numerical analysis were first conducted, and the numerical model was validated by comparing the experimental results to the analysis results. Subsequently, the seismic performance was investigated using a 100-m-long rehabilitation pipe model under earthquake-induced ground deformation. The novel low-friction rehabilitation pipe drastically reduced the strain acting on the lining pipe, indicating that the lining pipe is less likely to be damaged by earthquakes.

Keywords: bending test; cured-in-place pipe; FEM; low-friction pipe; pipe rehabilitation; seismic performance

1. Introduction

In Japan, many water pipelines were rapidly developed during the period of high economic growth (1950s-1970s) to satisfy the increasing water demand, and are still in use today. However, these water pipelines, which have been in operation for over 50 years since their installation, are now showing significant signs of aging.

In recent years, the number of water pipelines requiring renewal has increased. A traditional approach toward managing deteriorated pipelines is their replacement with new ones. However, the replacement of underground pipes typically requires open-cut excavation, resulting in high cost and disruptions to the surrounding environment. Moreover, replacement is particularly challenging in urban areas, owing to geographical constraints.

The cured-in-place pipe (CIPP) is a non-excavation pipe rehabilitation method, whereby a flexible polymeric lining pipe with thermosetting resin is inserted into the interior of the existing pipe with the aid of air pressure. The existing pipe and lining pipe are glued together and behave as a unified pipe. Compared with pipe replacement, CIPP is not subject to geographical constraints and has attracted attention for its potential in terms of reducing the

construction time and cost. Various studies on CIPP rehabilitation have been conducted, not only on water pipelines (Zhang *et al.* 2018, Hsu and Shou 2022), but also on sewage pipelines (Allouche *et al.* 2014), telecommunication pipelines (Okutsu *et al.* 2019, Tanaka *et al.* 2012, Yamazaki *et al.* 2017), and gas pipelines (Tafsirojjaman *et al.* 2022).

Considering the essential role of water pipelines in daily life and the need for their uninterrupted functionality even during earthquakes, the seismic safety of rehabilitation pipes is crucial (Argyrou *et al.* 2018, Izumi *et al.* 2016). Previous studies have confirmed that CIPP rehabilitation improves the axial stiffness and ductile axial behavior of water pipelines, allowing them to withstand earthquake-induced ground deformation (Zhong *et al.* 2014, Zhong *et al.* 2017, Bouziou *et al.* 2012) and continued axial loading (Jeon *et al.* 2024). Therefore, the CIPP rehabilitation method is expected to improve seismic resistance.

Ductile cast iron pipes, which are widely used in old Japanese water pipelines, are sufficiently strong to withstand earthquakes. During earthquakes, the damage is concentrated at the joints connecting the pipes. Consequently, because the joints in old water pipelines lack an anti-pullout function, joint detachment and water leakage may occur during earthquakes (Kumaki and Miyajima 2012). Ishizeki and Miyajima (2020) conducted tensile tests on a CIPP pipe with a non-seismic joint without an anti-pullout function, and confirmed that the CIPP rehabilitation

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pipe can prevent joint pull-out, because the ductile iron pipe and lining pipe are glued together.

Generally, lining pipes are glued to existing pipes by resin (Zhong *et al.* 2018). In previous studies on the CIPP rehabilitation pipe, the existing pipe and the lining pipe were assumed to be glued together (Ishizeki and Miyajima 2020). Under this assumption, even if the joint breaks, the lining pipe can resist tensile deformation because the existing pipe and lining pipe are glued together. Previous research has shown that the CIPP rehabilitation pipe prevents joint pull-out, which means that the lining pipe resists the tensile force on its own after the joint breaks. Therefore, the lining pipe may be damaged if the tensile force is excessive.

With this background, a novel low-friction CIPP rehabilitation pipe was developed in this study. A friction-reducing layer was inserted between the existing pipe and the lining pipe to reduce the excessive strain transmitted from the existing pipe to the lining pipe during earthquakes. Moreover, this study investigated the performance of the low-friction rehabilitation pipe under earthquake-induced ground deformation using three-dimensional nonlinear finite element analysis.

In the seismic design of underground pipelines, the seismic performance is determined based on the response displacement method (Japan Water Works Association 2009). This method has also been used by previous studies that evaluated the seismic performance of CIPP rehabilitation pipes (Argyrou *et al.* 2018, Okutsu *et al.* 2019, Tanaka *et al.* 2012, Yamazaki *et al.* 2017), where the existing pipe and lining pipe were modeled by the two-dimensional beam elements located in parallel. The effect of the surrounding soil was modeled by two soil springs in the normal and tangential directions, and the interaction between the existing and lining pipes was also modeled by two springs in the normal and tangential directions. While this modeling approach is convenient, it lacks the detailed modeling of the contact and friction between existing pipes and lining pipes, because it ignores the actual three-dimensional shape.

In this study, glued-type and low-friction rehabilitation pipes were considered, therefore, the accurate modeling of the interaction between existing pipes and lining pipes is an important consideration.

Moreover, this study used three-dimensional shell elements to model the existing and lining pipes, and the interaction between the existing pipes and the lining pipes was modeled using contact analysis, with consideration to the glue and friction. Because few previous studies have conducted numerical analysis with consideration to the contact and friction between existing and lining pipes (EI-Sawy and Moore 1998, Shou and Chen 2018, Furukawa *et al.* 2015), the analysis model was validated before evaluating the seismic performance of the novel rehabilitation pipe.

The rest of this paper is structured as follows. Section 2 provides an overview of the structures of conventional glued and novel low-friction rehabilitation pipes. Section 3 describes the bending tests and numerical analysis for the two rehabilitation pipe types. Analytical models for the two rehabilitation pipes were developed using the three-

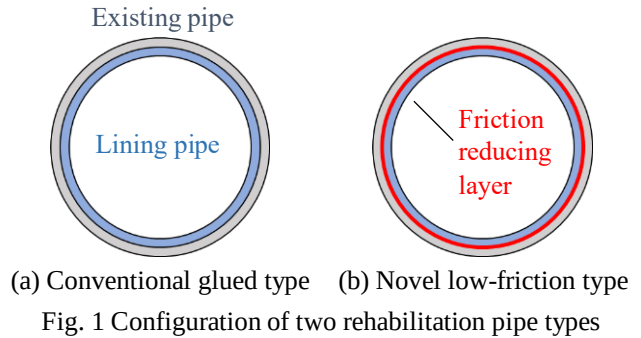


Fig. 1 Configuration of two rehabilitation pipe types

dimensional nonlinear finite element method with the aid of the contact analysis function, and the validity of the analysis models was confirmed by comparing the experimental and analysis results. Section 4 presents the three-dimensional nonlinear finite element analysis that was conducted to calculate the displacement and strain of the existing and lining pipes against the earthquake-induced ground deformation. The novel low-friction rehabilitation pipe was validated by comparing the response of the conventional glued-type pipe to that of the novel low-friction rehabilitation pipe.

2. Conventional glued-type rehabilitation pipe and novel low-friction rehabilitation pipe

The configuration of the conventional glued-type and novel low-friction rehabilitation pipes is shown in Fig. 1. The existing pipe was assumed to be made of ductile iron, which is commonly used in Japanese water supply systems, while the lining pipe was the newly developed pipe, consisting of an outer reinforcement layer formed cylindrically by adding thermoplastic resin to glass fiber composite felt, and an inner covering layer coated with polyester nonwoven fabric and polyethylene film. The lining pipe is designed to withstand soil pressure itself. In the conventional rehabilitation pipe, the existing pipe and the lining pipe were adhered together. In contrast, the novel low-friction pipe featured a thin friction-reducing layer placed between the existing pipe and the lining pipe. The friction-reducing layer is expected to reduce the earthquake-induced transfer of deformation from the existing pipe to the lining pipe, and thus prevent excessive strain in the lining pipe and minimize potential damage.

3. Bending test and finite element analysis for conventional and novel rehabilitation pipes

3.1 Test specimens and testing procedure

The layout diagram of the bending test, considering a conventional rehabilitation pipe specimen as an example, is shown in Fig. 2. In the low-friction rehabilitation pipe specimen, a friction-reducing layer was placed between the existing pipes and the inner pipe.

Two pipes were used as the existing pipes, each with a length of 500 mm, outer diameter of 271 mm, and thickness

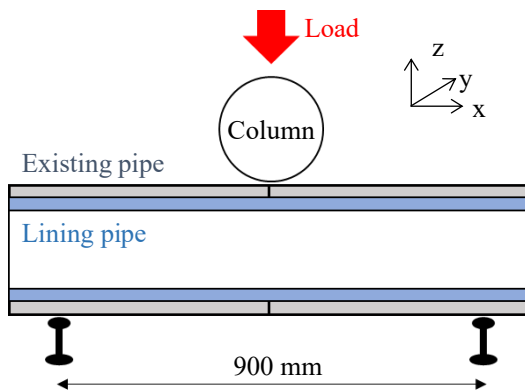


Fig. 2 Layout of experimental setup in bending test (example of conventional glued-type rehabilitation pipe)

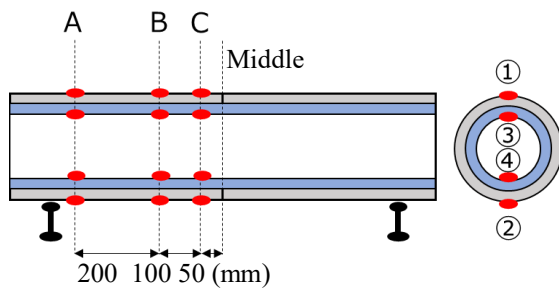


Fig. 3 Strain measurement positions

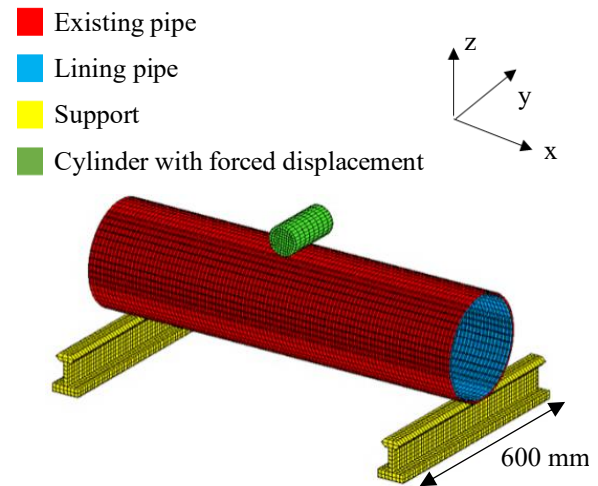
of 8.5 mm, arranged in series. The total length of the existing pipes was 1000 mm, and joints did not exist between the two pipes, which were simply in contact with each other. The inner pipe was a single pipe with a length of 1000 mm, outer diameter of 254 mm, and thickness of 3.3 mm. The total length of both the existing and rehabilitated pipes was 1000 mm.

The specimens were positioned on top of two rail steels (supports) with a spacing of 900 mm. A cylinder (diameter of 75 mm, height of 150 mm) was placed on the upper center of the specimen, and a vertical downward displacement of 50 mm was applied using a universal testing machine at the loading rate of 5 mm/min. The reaction force from the cylinder was measured, and the load-displacement relationship was recorded.

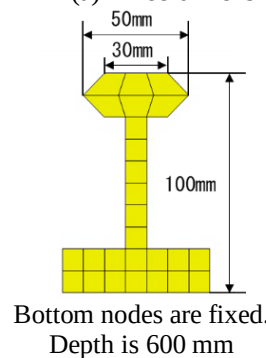
Additionally, as shown in Fig. 3, strain gauges were installed to measure the strain-displacement relationship of the specimens. The four strain gauges were placed on the top and bottom of the existing pipe, and top and bottom of the inner pipe, at three locations, A, B, and C.

3.2 Analysis model and analysis procedure

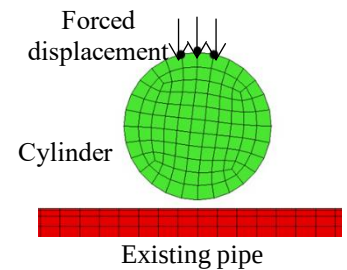
The 3D nonlinear finite element method, which accounts for finite deformations, was employed in the analysis. The analytical model is presented in Fig. 4, and the dimensions are outlined in Table 1. The existing pipe and lining pipe are modelled using nonlinear 3D shell elements, employing a mesh with 100 divisions in the axial direction and 48 divisions in the circumferential direction. Two supports, where the rehabilitation pipe is placed, were modelled using solid elements, each side measuring



(a) Three-dimensional view of analysis model



(b) Support



(c) Nodes where vertical displacement is forced

Fig. 4 Analysis model

Table 1 Test specimen dimensions

Existing pipe	Diameter (mm)	271
	Length (mm)	1000
	Thickness (mm)	8.5
Lining pipe	Diameter (mm)	254
	Length (mm)	500 (two pipes)
	Thickness (mm)	3.3
Support	Height (mm)	100
	Depth (mm)	600
Cylinder	Diameter (mm)	75
	Length (mm)	150

approximately 10 mm. The cylinder was also modelled with solid elements, divided into 28 divisions circumferentially and eight divisions in the depth direction.

Table 2 lists the density, Young's modulus, and Poisson's ratio for the existing pipe, lining pipe, supports, and cylinder. The existing and inner pipes were assumed to be elastic-plastic, as shown in Fig. 5, while the supports and cylinder were assumed to be elastic. The yield criteria were determined based on the Mises stress.

The interface between the existing and lining pipes was assumed to be in the glued state under the initial condition. When either the tensile or shear stress exceeds the tensile or shear strength, the glue is assumed to break, transitioning into the contact state. For the conventional type, the tensile

Table 2 Material properties

	Existing pipe	Lining pipe	Support Cylinder
Density (ton/mm ³)	7.20×10^{-9}	1.60×10^{-9}	7.28×10^{-9}
Young's modulus (N/mm ²)	1.62×10^5	1.05×10^4	2.00×10^5
Poisson's ratio	0.28	0.19	0.28
Yield strength (N/mm ²)	270	235	—

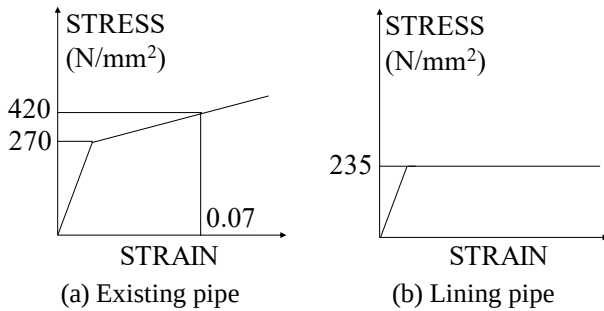


Fig. 5 Stress-strain relationship

and shear strength were set to 6.967×10^{-1} N/mm², with a friction coefficient of 0.52 after the glue breaks. For the novel low-friction type, the tensile and shear strength were set to 4.37×10^{-3} N/mm², with a friction coefficient of 0.04 after the glue breaks. The tensile and shear strength values were determined through experiments. In these tests, the existing pipe was fixed while a load was applied to the lining pipe along the axial direction of the pipe. The load at which the lining pipe began to slide was recorded, and the strength was calculated by dividing this load by the contact area. The same value was used for both tensile and shear strength. The friction coefficient after the glue breaking was determined based on the experiment. The difference between the conventional and novel rehabilitation pipes is the difference in the tensile and shear strength when the glue breaks, and in the friction coefficient after the glue breaks. Contact between the two existing pipes, between the existing pipe and support, and between the existing pipe and the cylinder was considered, and resistance against compression and friction (friction coefficient of 0.2) was assumed if contact existed. The general value of the friction coefficient between steel and ductile cast iron was adopted (American Institute of Physics, 1972). The contact analysis parameters are summarized in Table 3.

The coordinate system was established as shown in Fig. 4(a), with the x, y, and z axes defined accordingly. The bottom surface of the support points had displacement constraints in the x-, y-, and z-direction (Fig. 4(b)). Gravity acceleration (9806 mm/s²) was applied vertically downward to all nodes. Additionally, a vertical downward displacement of 50 mm was imposed incrementally on the nodes of the cylinder in 50 steps (Fig. 4(c)). Similar to the bending test, the vertical reaction force on the cylinder and the axial strain of the existing and rehabilitated pipes were calculated.

3.3 Experimental and analysis results

The comparison of the load-displacement relationships

Table 3 Contact parameters

Between existing and lining pipes	Conventional glued type	Tensile strength (N/mm ²)	0.6967
		Shear strength (N/mm ²)	0.6967
		Friction coefficient after breaking of glue	0.52
	Novel low- friction type	Tensile strength (N/mm ²)	4.37×10 ⁻³
		Shear strength (N/mm ²)	4.37×10 ⁻³
		Friction coefficient after breaking of glue	0.04
Friction coefficient between existing pipe and existing pipe, cylinder, and support		0.2	

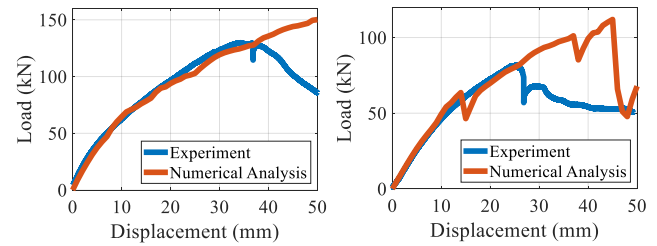


Fig. 6 Load-displacement relationship

between the experiment and the numerical analysis is shown in Fig. 6 for the two rehabilitation pipes. The numerical analysis effectively reproduced the experimental results from the initiation of loading and up to the maximum load for both rehabilitation pipes. The analysis model also captured the observed trend of the lower load for the novel low-friction type compared with the conventional glued type. The reason why the load continues to increase in the analysis is that the post-yield stiffness of both the existing and the lining pipes are modeled as either positive or zero as shown in Fig. 5, which means that the model does not account for softening behavior. Additionally, the model does not consider cracks in the pipes and therefore cannot represent the loss of stiffness caused by cracking. Since the strain levels in the pipes under seismic ground deformation, as discussed in the following section, are far smaller than the strain levels at the maximum load, this modeling approach achieves sufficient accuracy by effectively reproducing the results up to the maximum load.

Fig. 7 shows the shape of the test specimen when the maximum load was reached, and the shape of the analysis model when the same displacement as that in the experiment was applied (conventional glued type: 35 mm, novel low-friction type: 25 mm). In the experiments, while a small opening of the existing pipes was observed in the case of the conventional type, a significant opening was observed for the low-friction type. The analysis confirmed the opening of the existing pipes in both the conventional and low-friction type, but with a smaller opening of approximately 5 mm for the conventional type and a larger opening of approximately 20 mm for the low-friction type. The analysis successfully reproduced the larger opening of the existing pipes in the low-friction type. Additionally, both in the experiments and the analysis, the cylinder penetrated the existing pipes to a lesser degree in the low-friction type compared with the conventional type.

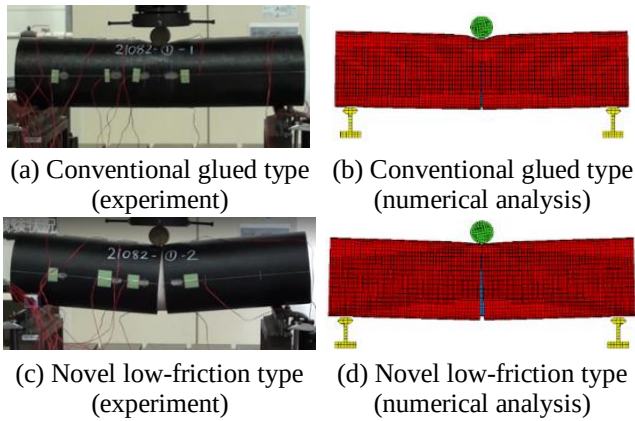


Fig. 7 Appearance of test specimen when reaching maximum load and analysis model when same displacement as in experiment was applied (conventional glued type: 35 mm, novel low-friction type: 25 mm)

Fig. 8 compares the axial strain-displacement relationships. Strain gauges were installed at four locations in the A, B, and C cross-sections, respectively. The strain in the axial direction was measured as shown in Fig. 3. Because the analysis reproduced the load-displacement relationship only up to the maximum load, the strain-displacement relationships up to the displacement at the time of reaching the maximum load were compared (conventional glued type: 35 mm, novel low-friction type: 25 mm). Except for point No. 4 in Fig. 8 (a), (b) and points No. 3 and 4 in Fig. 8 (e), (f) for the conventional rehabilitation pipe, the experimental and analytical results generally exhibit similar trends. The analysis successfully replicated the smaller strain observed in the low-friction type compared with the conventional type.

In Fig. 8(a), Point No. 4 corresponds to the strain measured at the bottom of the lining pipe near the left support. The reason for observing compressive strain in the experiment is not fully understood, but it is possible that the strain gauge was affected by the compressive force caused by the support.

The reason for the significant differences in strain variations observed in gauges No. 3 and No. 4 in the experimental results shown in Fig. 8(e), compared to other experiments and the FEM results in Fig. 8(f), remains unclear. Further investigation is necessary to understand the behavior of gauges No. 3 and No. 4 in Fig. 8(e).

As shown in Fig. 8 (i), (j), (k), (l), the tensile strain occurred at gauge No. 1 in the C cross-section because the loading cylinder presses the existing pipe vertically downward and this action induces tensile strain in the existing pipe around the loading cylinder.

4. Seismic performance evaluation of novel low-friction rehabilitation type

4.1 Overview

After the validation of the modeling approach as described in the previous section, numerical analysis was

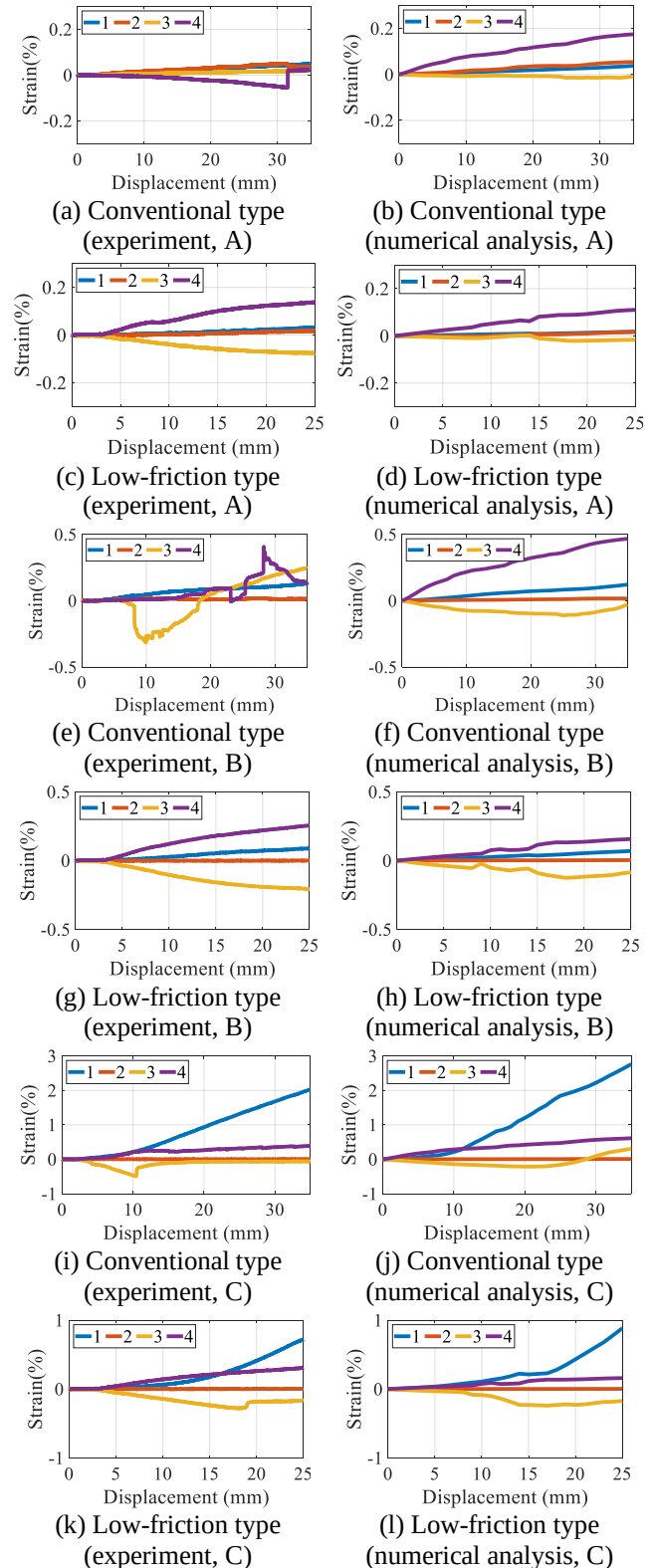


Fig. 8 Comparison between strain-displacement relationship in experiment (left) and numerical analysis (right) (1: top of existing pipe, 2: bottom of existing pipe, 3: top of inner pipe, 4: bottom of inner pipe)

conducted for a pipeline with a length of 100 m subjected to earthquake-induced ground deformation. Two rehabilitation pipes, the conventional and novel low-friction pipes, were

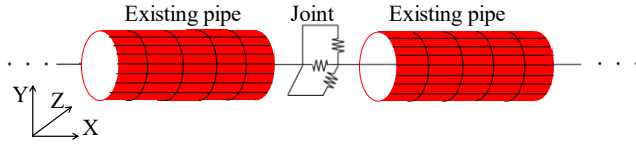


Fig. 9 Numerical analysis model of existing pipes connected by joints modeled by springs

considered. Following the procedure of the response displacement method outlined in the Guidelines by the Japan Water Works Association (2009), the earthquake-induced ground deformation was input into the existing pipes through ground springs, and the responses of the rehabilitation pipes were calculated. The objective of this analysis was to verify the performance of the low-friction rehabilitation pipe by comparing its response to that of the conventional rehabilitation pipe.

4.2 Analysis model

4.2.1 Existing and lining pipes

An overview of the analysis model and its axis are shown in Fig. 9. A total length of 100 m was achieved by connecting 20 existing pipes, each with a length of 5 m, using joints modeled by springs. A lining pipe with a length of 100 m was positioned inside the existing pipes.

Both the existing pipe (diameter of 200 mm, thickness of 8.5 mm) and the lining pipe (diameter of 183 mm, thickness of 3.3 mm) were modeled using 3D shell elements. The models were divided into 100 segments in the axial direction and 16 segments in the circumferential direction.

4.2.2 Ground spring

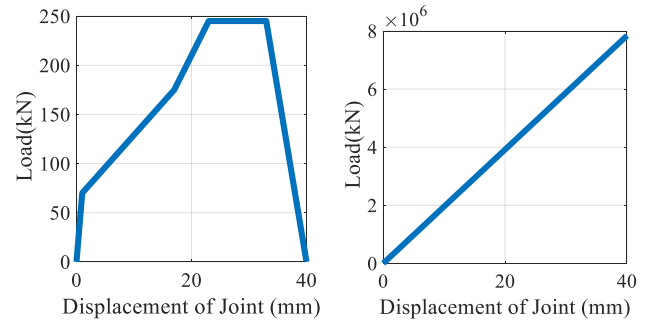
The influence of the ground was considered by using ground springs in three directions, as shown in Fig. 10. Ground springs were attached to each node of the existing pipes. The stiffness coefficient of the ground springs was determined using Eqs. (1) and (2) in accordance with the guidelines of the Japan Water Works Association (2009).

$$K_{g1} = C_1 \frac{\gamma_t}{g} V_s^2 \text{ for X direction} \quad (1)$$

$$K_{g2} = C_2 \frac{\gamma_t}{g} V_s^2 \text{ for Y, Z directions} \quad (2)$$

Here, K_{g1} (N/m²) and K_{g2} (N/m²) represent the stiffness coefficients of the ground springs per unit pipe length in the pipe axis direction and perpendicular-to-axis direction, respectively, γ_t (N/m³) is the unit weight of the soil, g (m/s²) is the gravitational acceleration, V_s (m/s) is the shear wave velocity of the surface soil. According to the guidelines, the general value for C_1 is approximately 1.5, and that for C_2 is approximately 3.0 (Japan Water Works Association 2009).

Assuming a unit weight of 15.68 kN/m³ for the soil and a shear wave velocity of 100 m/s for the surface soil, the stiffness coefficient of the ground springs in the axial and perpendicular-to-axis directions becomes $K_{g1}=1500$ kN/m² and $K_{g2}=3000$ kN/m², respectively.



(a) Pipe axis direction (tension side in X direction) (b) Direction perpendicular to pipe axis (Y, Z directions)

Fig. 10 Load-displacement relationship of joint

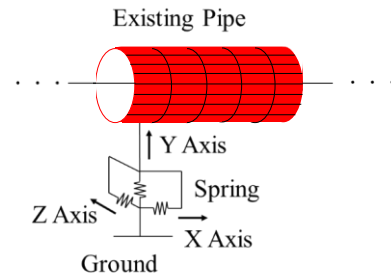


Fig. 11 Ground springs attached to existing pipe

4.2.3 Joint

The joint connecting adjacent existing pipes was represented using three springs, one in the pipe axis direction (X) and two in the orthogonal directions perpendicular to the pipe axis (Y, Z), as shown in Fig. 9. The load-displacement relationship of the spring in the X direction on the tensile side is shown in Fig. 10(a), and was modeled based on the experimental value of a joint used in the old pipes. On the compression side, two contacting existing pipes resisted each other. The spring constant of the Y and Z directions was set to 1.96×10^5 N/mm, as shown in Fig. 10(b), which is sufficiently large for preventing the existing pipes from separating.

4.2.4 Earthquake ground displacement

In this analysis, earthquake-induced ground deformation was applied to the existing pipes through ground springs. It was assumed that a uniform surface soil of sand (shear wave velocity $V_{s1} = 100$ m/s, thickness $H = 11.8$ m) was deposited over bedrock with a shear wave velocity of $V_{s2} = 300$ m/s. The natural period of the surface soil, determined based on a quarter-wave law, is $T_g = 4H/V_{s1} = 0.47$ s. The wavelength of the surface soil is $L_1 = 4H = 94$ m, and the wavelength at the bedrock is $L_2 = T_g V_{s2} = 141$ m. Consequently, the wavelength L of the ground deformation, calculated from Eq. (3) (Japan Water Works Association, 2009), is $L = 70.7$ m.

$$L = \frac{2L_1 L_2}{L_1 + L_2} \quad (3)$$

Next, it is assumed that the pipeline is buried at a depth $z = 0.8$ m from the ground surface. The displacement amplitude of the ground deformation was determined using Eq. (4) (Japan Water Works Association 2009), resulting in

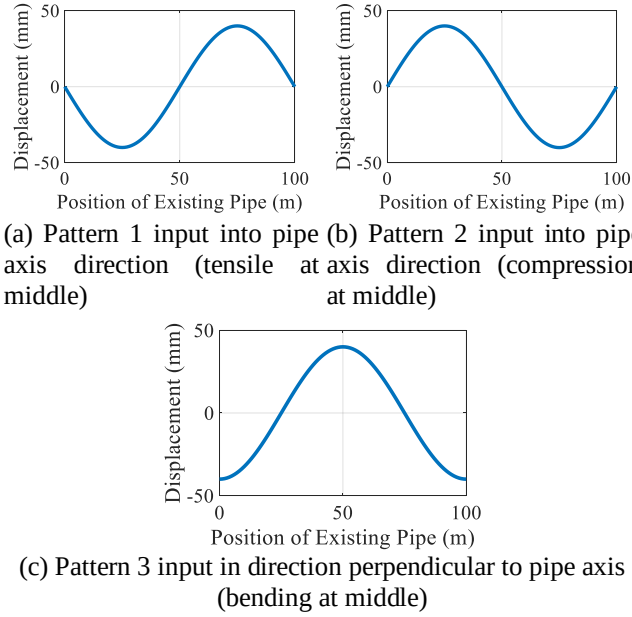


Fig. 12 Three patterns of ground displacement distribution

$U_G = 57$ mm.

$$U_G = U_h(z) = \frac{2}{\pi^2} S_v T_G \cos \frac{\pi z}{2H} \quad (4)$$

where $U_h(z)$ represents the horizontal displacement amplitude of the ground at a depth z (m), and S_v is the velocity response spectrum of the design ground motion. This study used the design response spectrum for a Level 2 earthquake.

Next, the obtained ground deformation, with an amplitude of 57 mm and wavelength of 70.7 m, was applied at a 45° angle to the axis of the pipeline, because the axial strain of the pipe becomes maximum at this angle. The apparent amplitudes and wavelengths of the ground deformation in the axial and perpendicular-to-axis directions were determined by dividing the ground displacement amplitude U_G by $\sqrt{2}$ and multiplying the wavelength L and $\sqrt{2}$ assuming a plane wave, resulting in an apparent amplitude of 40 mm and apparent wavelength of 100 m.

Based on these considerations, ground displacement with an amplitude of 40 mm and wavelength of 100 m was applied to the 100-m-long pipeline in 50 steps in this numerical analysis.

4.3 Three ground displacement patterns

The three ground displacement patterns shown in Fig. 12 were applied to the existing pipe. The horizontal axis is the distance from the left end of the pipeline. The displacement of Patterns 1 and 2 was input into the pipe axis direction (X), and that of Pattern 3 was input into the direction perpendicular to the pipe axis (Y). Pattern 1 represents the ground displacement when the tensile strain is maximum at the midpoint. Pattern 2 represents the ground displacement when the compressive strain is maximum at the midpoint. Pattern 3 represents the ground

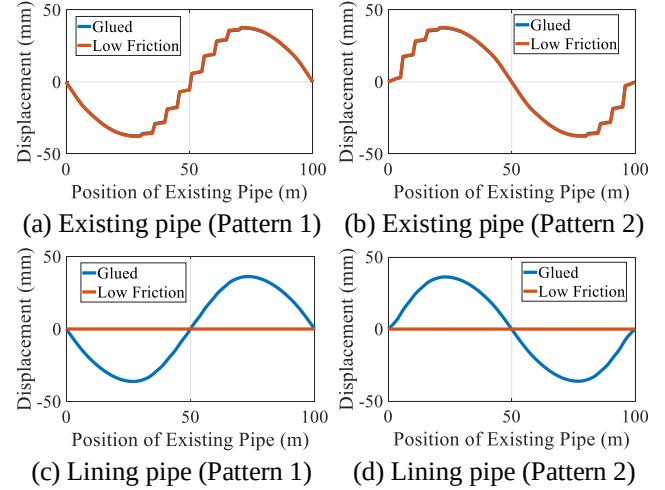


Fig. 13 Displacement distribution in axial direction (Patterns 1, 2)

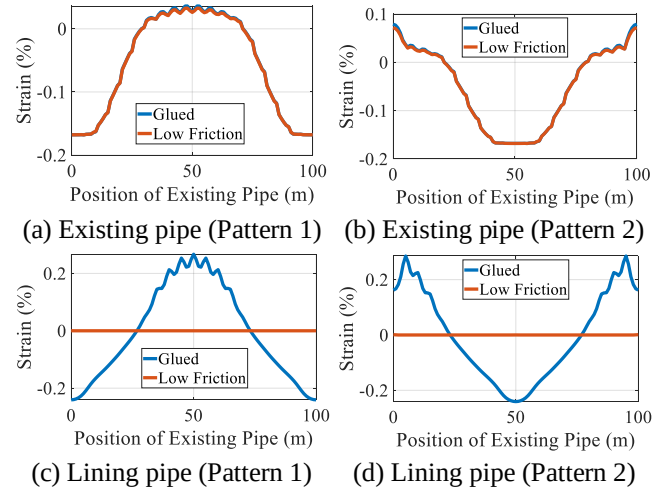


Fig. 14 Strain distribution in pipe axis direction (Patterns 1, 2)

displacement when the bending strain is maximum at the midpoint. The ground displacements for Patterns 1 to 3 were input into the two rehabilitation pipe models, namely, the conventional glued and low-friction models. By comparing the displacements and axial strains of the existing and lining pipes, the performance of two rehabilitation pipes was investigated.

4.4 Analysis results

4.4.1 Ground displacement applied in pipe axis direction (Patterns 1 and 2)

Figs. 13 and 14 show the displacements and strains of the existing and rehabilitated pipes in the pipe axis direction (X) after applying ground displacement with Patterns 1 and 2 in the X direction.

Regarding the displacement and strain of the existing pipe, there is little difference between the conventional and low-friction rehabilitation pipes in both patterns. However, for the displacement and strain of the lining pipe, it can be observed that, with both patterns, the low-friction

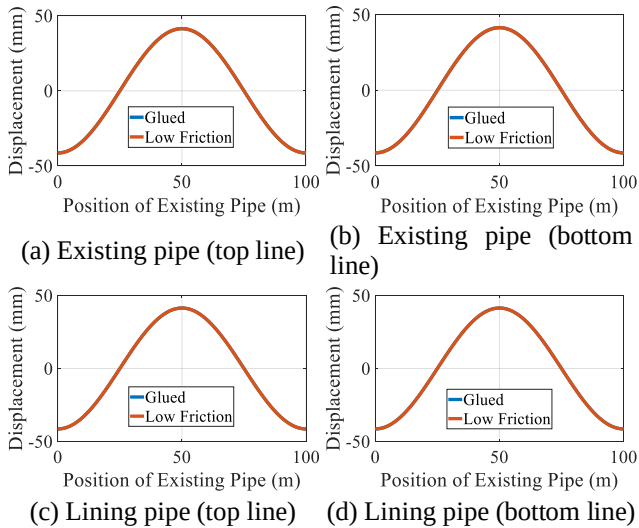


Fig. 15 Displacement distribution in direction perpendicular to pipe axis (Pattern 3)

rehabilitation pipe exhibited significant reduction compared with the conventional pipe.

The strain of the conventional lining pipe fluctuated in the range of 30-70 m with Pattern 1, and in the range of 0-20 m and 80-100 m with Pattern 2. This is because the joints connecting adjacent existing pipes yield owing to tensile deformation, and the lining pipe must resist the tensile force on its own, because the existing pipe and lining pipe are glued. For the low-friction rehabilitation type, the glue between the existing and lining pipe broke quickly, and it was unlikely for the lining pipe to be affected by ground deformation. For this reason, the strain of the lining pipe was very small in the low-friction rehabilitation pipe.

In the low-friction rehabilitation pipe, the existing pipe may open at the joint (Fig. 13), potentially exposing the lining pipe to direct soil pressure. However, since the material of the lining pipe has been designed to withstand direct soil pressure itself, the exposure to soil pressure is not an issue. As shown in Fig. 14 (c) and (d), the strain in the lining pipe is not excessively large even for the conventional rehabilitation pipe. However, if large ground displacements or localized large ground strains occur, the conventional rehabilitation pipe could experience excessive strain. In such scenarios, the strain reduction effect of the low-friction rehabilitation pipe on the lining pipe can be considered highly beneficial.

4.4.2 Ground displacement applied in perpendicular-to-pipe-axis direction (Pattern 3)

Figs. 15 and 16 show the displacement in the Y direction and the strains in the X direction of the existing and lining pipes after applying ground displacement in Pattern 3. The results at the top and bottom of the pipes are shown. As can be seen, there is no significant difference in the displacement distribution or strain distribution between the conventional and low-friction rehabilitated pipes.

For ground displacement in the direction perpendicular to the axis, the existing pipe transmits deformation to the lining pipe by compressive force, which means that the

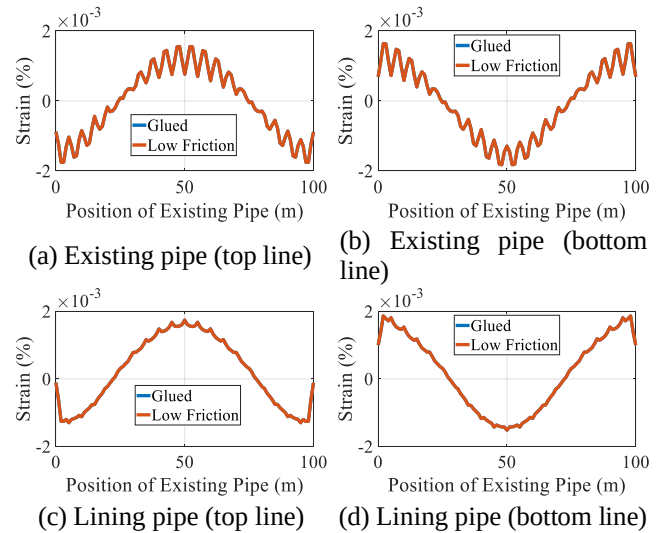


Fig. 16 Strain distribution in pipe axis direction (Pattern 3)

deformation of the existing pipe is easily transmitted to the lining pipe, even if it is a low-friction pipe. Therefore, the strain reduction effect was not observed.

In contrast, for the axial displacement, the existing pipe transmits deformation to the lining pipe by a frictional force, such that the deformation of the existing pipe is less likely to be transmitted to the lining pipe, and the strain of the lining pipe is reduced in the case of the low-friction type.

5. Conclusions

This study confirmed the effectiveness of a novel low-friction rehabilitation pipe over the conventional glued-type rehabilitation pipe against earthquake-induced ground deformation.

First, bending tests and finite element analysis were conducted for the conventional glued-type and novel low-friction rehabilitation pipes. The analysis revealed that there is good agreement between the load-displacement relationships, strain-displacement relationships, and overall shape at the maximum load in the experimental and simulation results. Therefore, the numerical modeling approach was validated.

Subsequently, the seismic performance of the two rehabilitation pipes was analyzed using the response displacement method. Based on the analysis results, the utility of the low-friction rehabilitation pipe is considered.

First, for Patterns 1 and 2, where earthquake-induced ground displacement is applied in the direction of the pipe axis, it was confirmed that the strain of the lining pipe in the low-friction rehabilitation pipe significantly decreased compared with the conventional pipe. This suggests that the low-friction type is less prone to failure caused by earthquake-induced ground displacement.

Secondly, with Pattern 3, where ground displacement was applied in the perpendicular-to-pipe-axis direction, there was almost no difference in the magnitude of strain compared with Patterns 1 and 2.

Even though the low-friction-type could not reduce the strain of the lining pipe with Pattern 3, the strain caused by the earthquake-induced ground displacement in the pipe axis direction (Patterns 1, 2) was more significant than that in the direction perpendicular to the pipe axis (Pattern 3). The low-friction rehabilitation pipe significantly reduced the strain of the lining pipe with Patterns 1 and 2.

In conclusion, the numerical analysis confirms that, by reducing the strain in the lining pipe, the low-friction rehabilitation pipe achieves better performance against earthquake-induced ground deformation in the pipe axis direction compared with the conventional pipe.

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