Integrated effects of combined manhole and sewer pipe countermeasures in liquefied ground using dynamic centrifuge model tests

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ABSTRACT: This study addresses the challenge of manhole and sewer pipe uplift caused by ground liquefaction during earthquakes, which is a critical issue for urban infrastructure resilience. The research aims to evaluate the integrated effectiveness of three seismic countermeasures: the Seismic Retrofitting Joint Manhole (SRM), which enhances flexibility at manhole-pipe connections; the floatless manhole method, which reduces excess pore water pressure using dissipation valves; and the lining pipe method, which internally reinforces aging pipes. Dynamic centrifuge model tests were conducted with various combinations of these methods. Results demonstrated that the floatless manhole method significantly suppressed manhole uplift, while the lining pipe method effectively suppressed pipe joint bending. The SRM method allowed flexible movement at connections, further contributed to uplift suppression. When all three measures were combined, both vertical displacement and bending strain were minimized, confirming their synergistic benefits. These findings provide practical insights for engineers and urban planners to enhance the seismic resilience of sewer systems in liquefaction-prone areas.

1 INTRODUCTION

In Tokyo, based on the characteristics of damage to sewerage facilities observed during past major earthquakes, technologies and construction methods for seismic retrofitting have been developed and applied to existing facilities to mitigate and prevent such damage. During the 1995 Hyogoken-Nanbu Earthquake, damage was particularly observed at the joints between sewer pipes and manholes, due to their different seismic responses. To address this, the "Seismic Retrofitting Joint Manhole (hereinafter referred to as SRM)" method (Figure 1) was developed and implemented, in which the connection between existing manholes and sewer pipes is modified to a flexible structure. This method ensures seismic performance against bending (bending angle of 5 degrees) and pull-out (displacement of 100 mm) under Level 2 seismic motion (CTRCO, 2021).

During major earthquakes, such as the 2004 Niigata Chuetsu Earthquake, the uplift of manholes due to ground liquefaction has emerged as a significant problem for urban sewerage systems (Figure 2). To address this, the floatless manhole method (CTRCO, 2022) was developed, which installs multiple dissipation valves on manhole walls to dissipate excess pore water pressure and suppress uplift during liquefaction (Nishiwaki, 2014; Tanaka and Terasako, 2018). While the effectiveness of this method has been confirmed for standalone manholes through centrifuge model tests (Matsuda et al., 2005), in practice, manholes are almost always connected to sewer pipes, and the influence of these connections on uplift behavior has rarely been considered (Suzuki, 2015). Previous studies by the authors (Muto et al., 2022) using dynamic centrifuge model tests have shown that connected pipes can significantly affect manhole uplift.

In addition to the floatless manhole method, the Tokyo Metropolitan Government has adopted the lining pipe method as a countermeasure against damage to aging sewer pipes (TMG, 2021). This method involves constructing a new pipe within the existing one using resin materials, thereby restoring or exceeding the strength of installed pipes. As a result, it is increasingly common for both floatless manhole and lining pipe countermeasures to be applied together in urban sewerage systems.

Recently, Suzuki et al. (2024) conducted centrifuge model tests on the combined application of the Floatless Manhole (hereinafter referred to as FM) method and the Lining Pipe (hereinafter referred to as LP) countermeasure and confirmed that this combination provides a certain level of effectiveness in mitigating manhole uplift and pipe deformation.

However, the combined effectiveness of these countermeasures, especially when integrated with new technologies such as the SRM—which enhances the flexibility of connections between manholes and sewer pipes to resist bending and pull-out during seismic events—has not been fully evaluated. The SRM method is designed to allow flexible movement at the connection, further preventing uplift of manholes and damage during earthquakes.

This study aims to comprehensively evaluate the integrated effects of the FM, LP, and SRM methods on the seismic performance of manhole-pipe systems in liquefied ground. A series of dynamic centrifuge model tests was conducted with various combinations of these countermeasures.

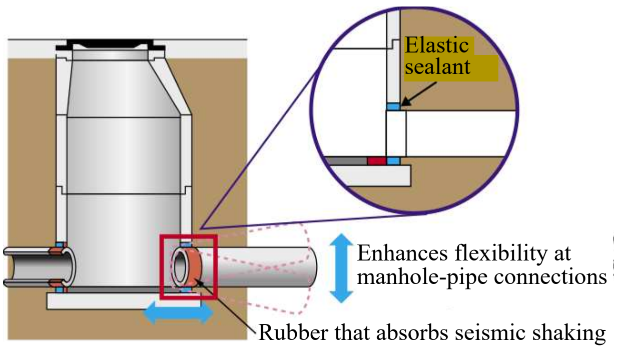

Figure 1. Seismic Retrofitting Joint Manhole (SRM).

Figure 2. An example of manhole uplift resulting from the 2004 Niigata Chuetsu Earthquake.

2 CENTRIFUGE MODEL TESTS

Centrifuge model tests were conducted under a 30g centrifugal force using a beam-type centrifuge with an effective radius of 2.6 m manufactured in-house by Nippon Koei Co., Ltd. (Figure 3). A waveform recorded by the Kobe Marine Observatory (NS component) during the 1995 Great Hanshin Earthquake was used as the input seismic excitation wave; its amplitude was adjusted so that the maximum input acceleration was 6.82 m/s^2 (Figure 4).

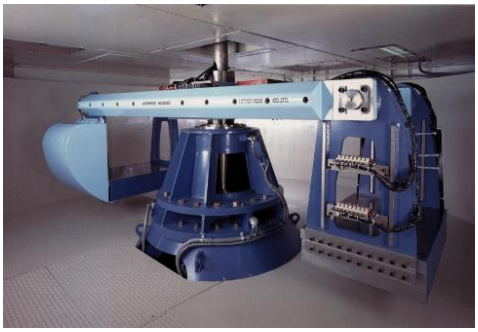

Figure 3. Nippon Koei centrifuge.

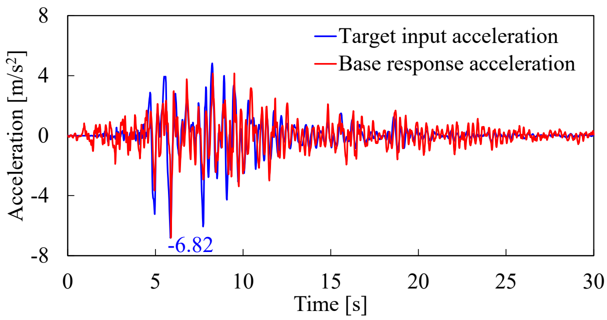

Figure 4. Input seismic wave.

2.1 Model preparation and test materials

Manhole–pipe models were constructed at a model/prototype scale of 1/30. Toyoura sand and #3 silica sand were used to simulate the liquefaction layer and foundation layer, respectively, in the test models; their physical properties are summarized in Table 1. The model ground was prepared in a 1000 × 400 × 250 mm rigid soil container to achieve a depth of 6.7 m (prototype scale) and a target relative density of 54% using the air pluviation method. Table 2 lists the dimensions of the manhole and pipeline models used in the tests, which were prepared at 1/30 scale based on prototypes with an outer diameter of 1390 mm and inner diameter of 700 mm, respectively.

The model ground was saturated by a methylcellulose solution (metolose) with a kinematic viscosity of 30 mm^2/s using the ground saturation method under a 7 g centrifugal force and monitored by a piezometer until the prescribed saturation was achieved.

A 10 mm layer of #3 silica sand with a model asphalt (for a prototype roadway thickness of 300 mm) was placed on top of the liquefaction layer to achieve an overburden pressure equivalent to that of the prototype road pavement. The average unit volume weight of this pavement section was γ_t = 15.671 kN/m^3.

Table 1. Physical properties of test materials.

Physical property	Toyoura sand	#3 silica sand
Maximum grain size, D_{max} [mm]	0.425	2
Mean grain size, D_{50} [mm]	0.169	1.46
Uniformity coefficient, U_c	1.43	1.47
Coefficient of curvature, U_c'	0.966	0.975
Minimum dry density, ρ_{dmin} [g/cm^3]	1.368	1.483
Maximum dry density, ρ_{dmax} [g/cm^3]	1.663	1.685
Density of soil particles, ρ_s [g/cm^3]	2.649	2.635

Table 2. Model component dimensions.

Dimension	Manhole		Sewer pipe	
	Proto-type	Model (1/30)	Prototype	Model (1/30)
Diameter [mm]	1390 (outer)	46.3 (outer)	700 (inner)	23.3 (inner)
Height [mm]	2300	76.7	-	-
Weight	3475 kg	128.7 g	899 kg	33.3 g
Length [mm]	-	-	Long: 2430 Short: 1200	Long: 81 Short: 40

2.2 Tests cases and outline of model tests

Table 3 lists the seven test cases considered in this study, and Figures 5, 6 and 7 present an outline of the model setup used in each case.

Table 3. Test cases.

Test case	Countermeasure	Model setup details
Case 1	Non-FM and FM Without pipeline	Two individual manholes one with and one without the FM
Case 2	Non-FM With pipeline	Conventional bell-and-spigot jointed pipes between two manholes without the FM
Case 3	FM only With pipeline	Case 2 with the FM on the two manholes
Case 4	FM+LP With pipeline	Case 3 with the LP in the pipes
Case 5	SRM only With pipeline	Case 2 with the SRM
Case 6	LP only With pipeline	Case 2 with the LP
Case 7	SRM+FM+LP With pipeline	Case 4 with the SRM

As shown in Figure 5, Case 1 was conducted on a manhole with the FM method and a manhole without the FM method (hereinafter referred to as Non-FM). In the manhole with FM, 12 excess pore water pressure dissipation valves were installed to confirm that the FM countermeasure (Figure 8) effectively dissipated the excess pore water pressure generated during an earthquake and prevents lifting of the manhole.

Case 2 was conducted to confirm the uplift and deformation behaviors of jointed pipes connecting two manholes (Non-FM); the sewer pipe configuration is illustrated in Figure 6. The total pipeline length was 607 mm (based on a prototype length of 18.21 m) with an inner diameter of 23.3 mm (based on a prototype diameter of 700 mm), comprising one short pipe section and seven long pipe sections. Each pipe segment was connected to the others using a thin coating of a silicone agent for the sole purpose of water sealing. The connection between the pipe and manhole was rigid.

In Case 3 (Figure 7), two manholes with the FM countermeasure were connected by the same pipeline configuration applied in Case 2.

In Case 4 (also Figure 7), the LP countermeasure was applied to the pipeline configuration used in Case 3.

Case 5 (Figure 6, Case 2 with the SRM), the SRM was applied to the connecting joint between pipeline and manhole to allow flexible movement at the connection, further preventing uplift and damage during earthquakes (Figure 1).

Case 6 (Figure 7, Case 2 with the LP), only the LP countermeasure was applied to pipeline.

Case 7 (Figure 7, Case 4 with the SRM), combination of the three methods (SRM, FM, LP) was applied to the manholes and pipeline.

The model sewer pipe joints are shown in Figure 9. Figure 10 presents photographs of the models prepared for each test case.

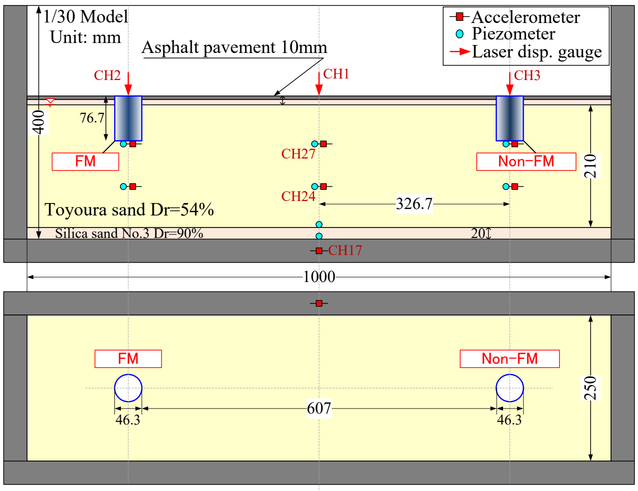

Figure 5. Centrifuge model setup (Case 1).

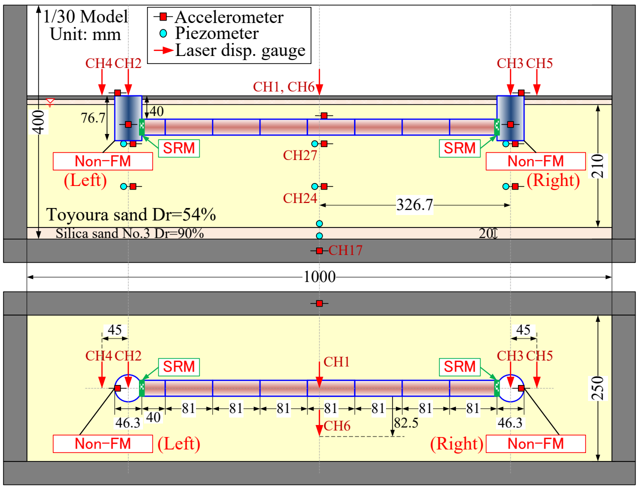

Figure 6. Centrifuge model setup (Cases 2 and 5).

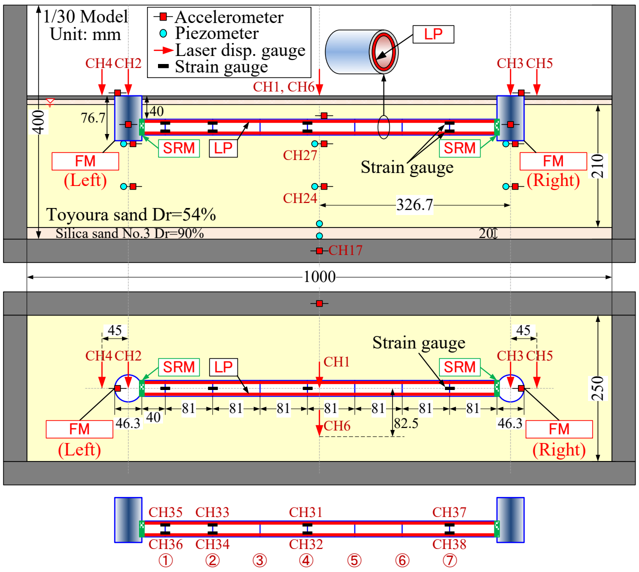

Figure 7. Centrifuge model setup (Cases 3, 4, 6 and 7).

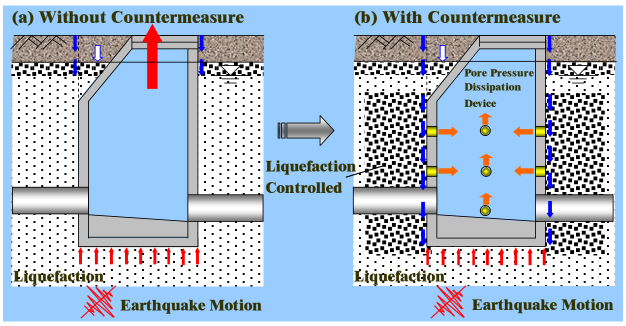

Figure 8. Manhole response of seismic motion in liquefied soil (a) with Non-FM and (b) with the FM countermeasure.

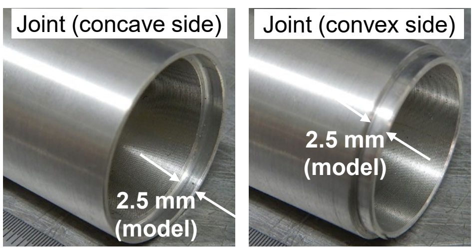

Figure 9. Example of pipe joints.

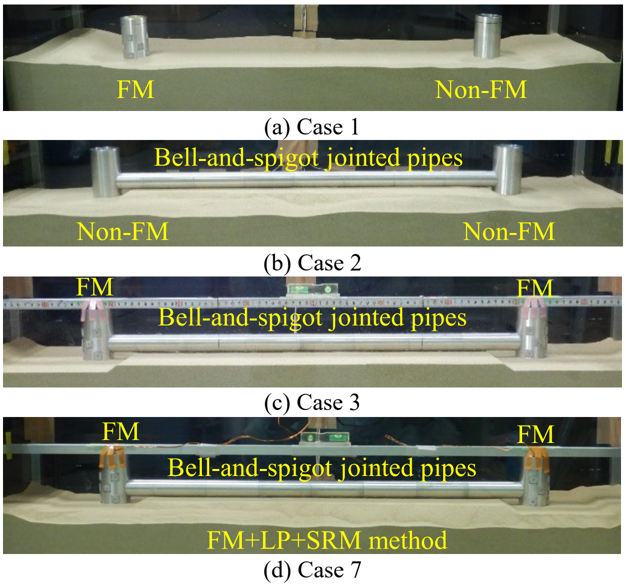

Figure 10. Prepared models.

2.3 Manhole and pipeline model

The manholes had an outer diameter of 1390 mm and a height of 2300 mm (prototype scale), and the sewer pipe had an inner diameter of 700 mm and a length of approximately 20 m (prototype scale). The manholes used in the model tests hereinafter referred to as left and right manhole, respectively.

Considering that the connection between the manhole and sewer pipe is typically fixed with mortar when no countermeasures are present, the model connection it was made with sealing tape such that the connection was sealed against water intrusion.

Holes were drilled in the manhole for the FM countermeasure to dissipate the excess pore water pressure, and vertical straws were provided in the manholes to allow the pore water pressure to be dissipated quickly. The drilled holes were laminated with a mesh material to prevent the entry of sand and soil (Figure 11).

Rounded polyvinyl chloride (PVC) sheets were used to line the interiors of the pipes, matching the use of PVC resin on construction sites. The thickness of the PVC sheet was 0.5 mm (on the model scale) such that the tensile stiffness of the model would be the same as that of the prototype material (Figure 12).

On the other hand, in the SRM for existing manholes, the gap at the connection between the manhole and the sewer pipe was adjusted so that the bending angle between them would be within ±5 degrees, and silicone resin was applied to provide flexibility (Figure 13). This is important for accommodating seismic movement and preventing damage during earthquakes.

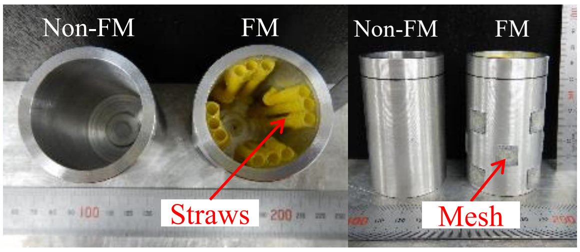

Figure 11. Manhole models.

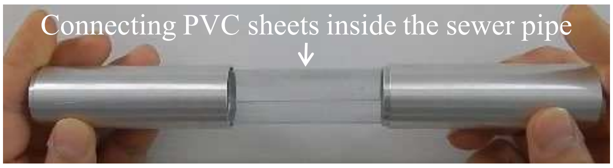

Figure 12. Pipe lining materials.

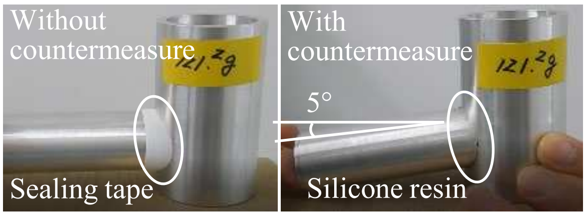

Figure 13. Connection between manhole and sewer pipe.

3 TEST RESULTS

All test results shown in this section are expressed using the prototype scale.

3.1 Ground liquefaction conditions

Figure 14 shows the base response acceleration and excess pore water pressure ratio for each test case. The maximum base response acceleration was approximately 6.82 m/s^2, matching the maximum input acceleration. The excess pore water pressure ratio ($\Delta u/\sigma_v'$) was obtained by dividing the excess pore water pressure Δu generated in the model ground by the effective overburden pressure σ_v'; when $\Delta u/\sigma_v' \geq 1$, the entire ground can be assumed to have completely liquefied.

3.2 Influence of sewer pipes

Figure 15 shows the time history of the vertical manhole displacement, focusing on the influence of the sewer pipes by comparing the results of the Non-FM of Case 1 and the left manhole of Case 2. The residual displacement of the manhole in Case 2 (Non-FM) was 29.4 cm less than that in Case 1 (Non-FM) owing to the downward force applied by the weight of the sewer pipes and the frictional resistance between the sewer pipes and the soil.

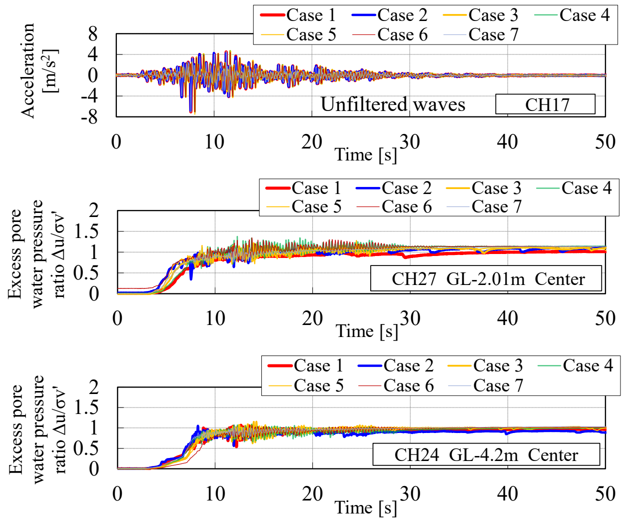

Figure 14. Base accelerations and excess pore water pressure ratios.

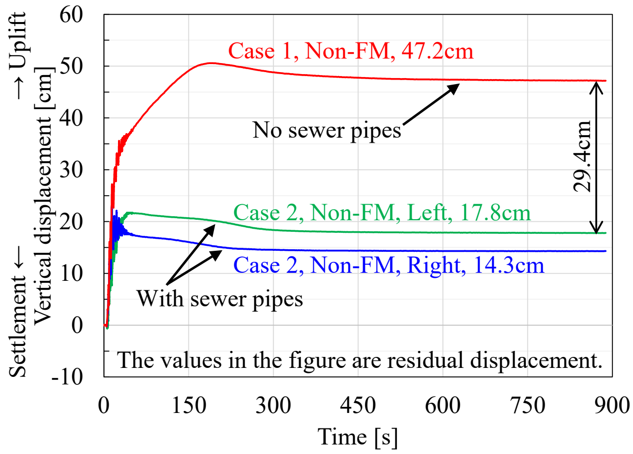

Figure 15. Vertical displacement of manhole (effect of sewer pipes).

3.3 Effect of each countermeasure

3.3.1 FM countermeasure

Figure 16 shows the time history of vertical manhole displacement with and without the FM countermeasure by comparing the results of Case 1, Case 2, and Case 3. To simplify the discussion, all cases except Case1 were compared in the amount of the left manhole. The residual displacement of the FM in Case 1 was 53.7 cm less than that of the Non-FM in the same case, confirming that the FM countermeasure suppressed manhole uplift. Furthermore, the residual displacement of the FM in Case 3 was 15.6 cm less than that of the Non-FM in Case 2, confirming that manhole uplift was suppressed by the FM countermeasure even when the sewer pipes were connected.

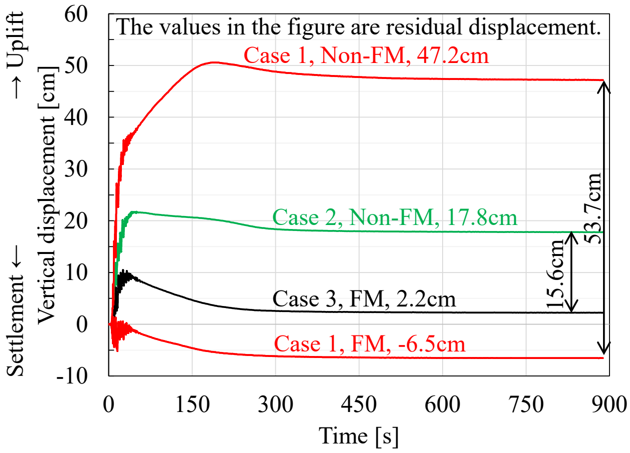

Figure 16. Vertical displacement of manhole (effect of the FM countermeasure).

3.3.2 LP countermeasure

Figure 17 shows the final conditions of the model sewer pipes after the tests were performed for Cases 2, 3, 6, and 4. In Case 2, bending was observed at the joint near the center of the sewer pipe. In Case 3, slight bending was observed at this joint. However, in Case 6 and 4, the lining installed inside the sewer pipe prevented the bending of the entire pipeline, confirming that sewer pipe bending can be suppressed during an earthquake.

Figure 18 shows the time history of the bending strains in the lining pipe in Case 6 and 4, indicating bending strains ranging from approximately -900 to +1000×10^{-6}. This range suggests that the lining pipe installed inside the sewer pipes indeed suppressed bending at the pipe joints, confirming the effectiveness of the lining in controlling pipe bending.

Figure 19 compares the time histories of the vertical manhole displacements with and without the LP countermeasure. The vertical displacement obtained in Case 6 was 11.7 cm less than that obtained in Case 2, demonstrating the effectiveness of the LP countermeasures. However, the vertical displacement owing to manhole uplift in Case 4 was nearly the same as that in Case 3 (a difference of 0.2 cm). The LP method's contribution to manhole uplift suppression was particularly evident in Case 6 (LP), which did not include the FM countermeasure. As shown in Figure 18, the amount of bending strain was smaller in Case 4 (FM+LP), which incorporated the FM method. This suggests that the application of this technique itself effectively suppresses manhole uplift.

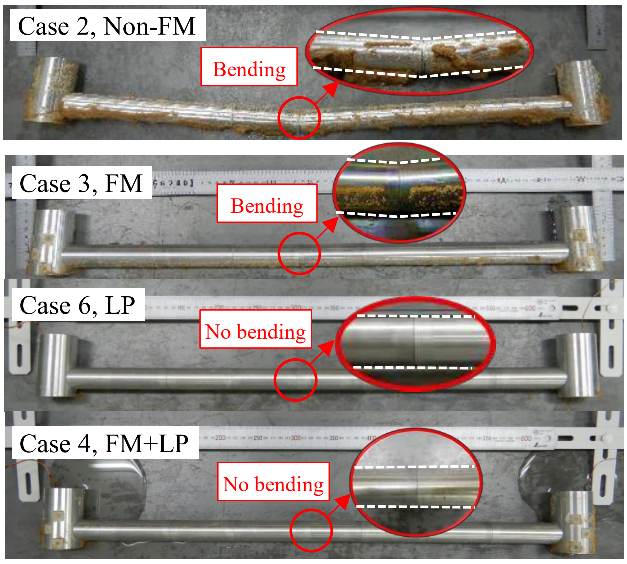

Figure 17. The states of the models after the tests.

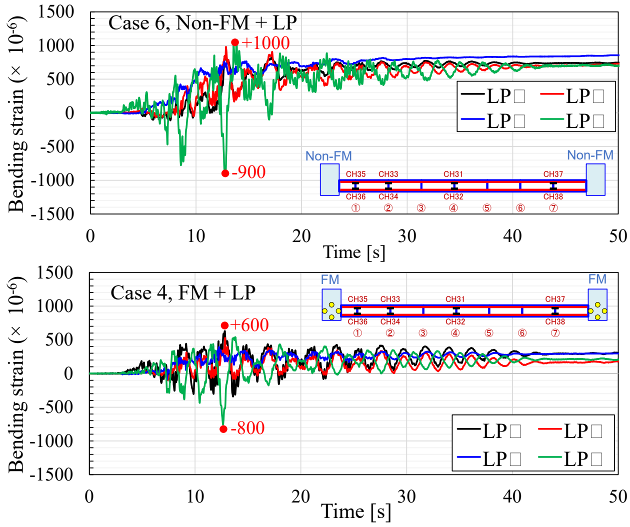

Figure 18. Time history of bending strain.

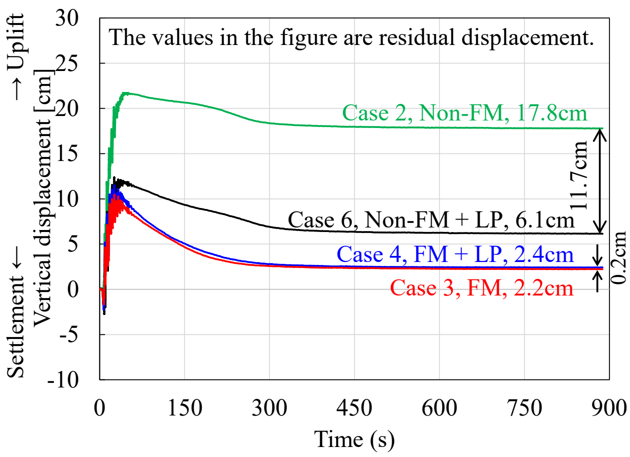

Figure 19. Vertical displacement of manhole (effect of the LP countermeasure).

3.3.3 SRM countermeasure

Figure 20 shows the time history of the vertical displacement of the manhole with and without the application of the SRM for existing manholes. As seen in Figure 20, the uplift of the manhole in Case 5 (SRM) was suppressed by 7.5 cm in terms of residual displacement compared to Case 2 (without SRM countermeasure). Although the SRM for existing manholes was originally developed to prevent damage at the connection between the manhole and the sewer pipe during earthquakes, this experiment confirmed that it also contributes to suppressing manhole uplift. This is presumed to be due to the changes in the coupled behavior between the manhole and the sewer pipe, as the flexible structure at the connection absorbs seismic motion. However, further investigation, including numerical analysis, is needed to clarify the mechanism of manhole uplift suppression.

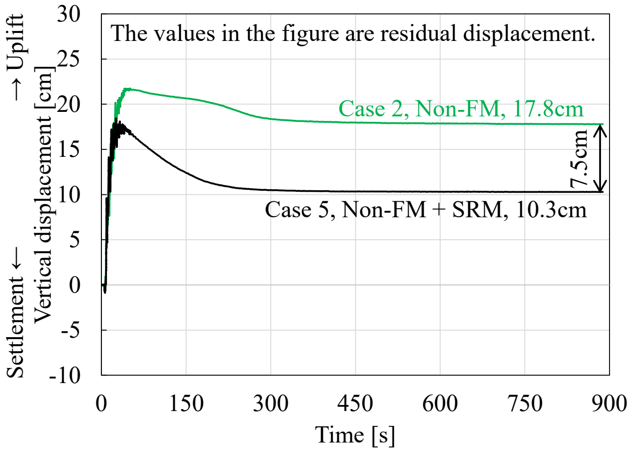

Figure 20. Vertical displacement of manhole (effect of seismic retrofitting joint manhole countermeasure).

3.3.4 Comparison of residual displacement of manholes due to combination of each countermeasure

Table 4 presents a summary of the residual displacements of manholes for all cases with sewer pipes, while Figure 21 shows the distribution of residual displacements (average of both manholes). For the comparison of residual displacements across all cases, the average value of both manholes was used for evaluation. From this figure and table, it was confirmed that combining multiple countermeasures tends to be more effective than applying the FM method alone.

Table 4. List of residual displacement of manholes.

Test case	Counter-measure	Left [cm]	Right [cm]	Average [cm]
Case 2	None	17.8	14.3	16.1
Case 3	FM	2.2	11.3	6.7
Case 4	FM + LP	2.4	8.1	5.2
Case 5	SRM	10.3	14.4	12.3
Case 6	LP	6.1	16.8	11.5
Case 7	FM + LP + SRM	5.2	2.2	3.7

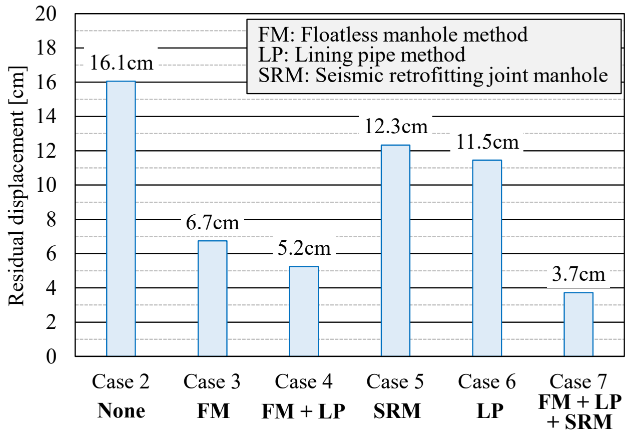

Figure 21. Residual displacement of manholes in each case (average of the left and right manholes).

Figure 22 shows the visualizations of the vertical displacement distribution based on the measured surface height after the tests.

In Case 2, both manholes (Non-FM) exhibited uplift that raised the connected pipeline as well as the ground above it. The displacement distributions of Cases 3, 4, 5 and 6 indicated less uplift than that of Case 2, showing the uplift suppression effect of the FM, SRM and LP. The displacement distributions in Case 7 showed less uplift than in all other cases, confirming that the combination of the FM, LP, and SRM countermeasures was effective in controlling both manhole and pipe uplift.

4 CONCLUSIONS

Seven dynamic centrifuge model test cases were conducted to evaluate the integrated effects of the FM, LP, and SRM methods on the seismic performance of manhole-pipe systems in liquefied ground. The results of this study can be summarized as follows.

(1) Compared to the manhole alone, integrating the manhole and sewer pipe into a single structure suppressed the amount of manhole uplift.

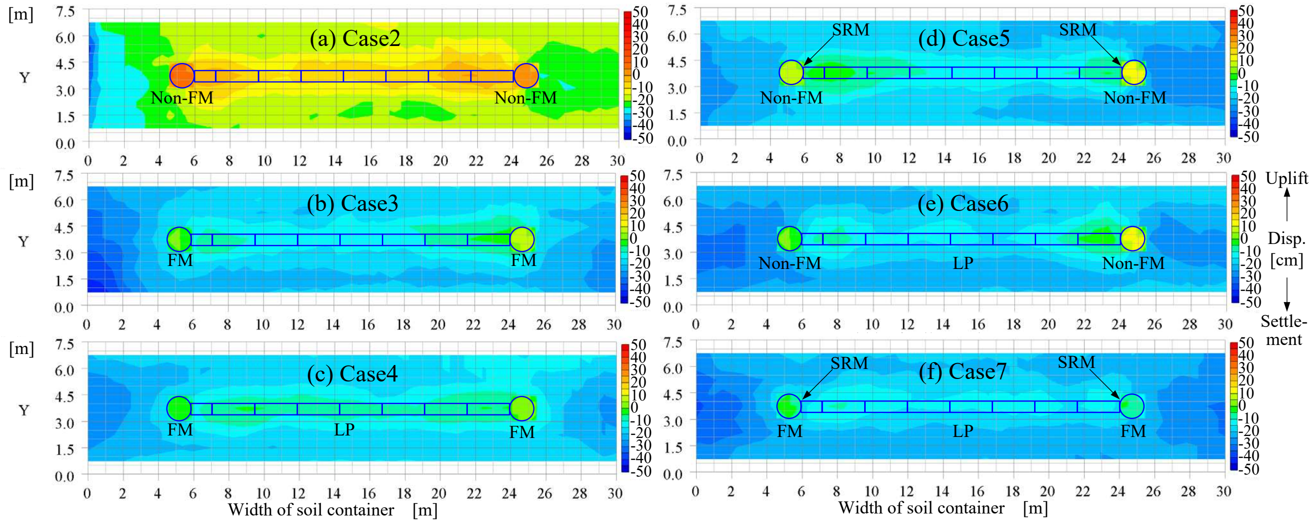

Figure 22. Vertical displacement distributions after each test.

(2) The FM method demonstrated an uplift suppression effect even when evaluated on the manhole alone; however, a greater effect was observed when the manhole and sewer pipe were integrated.

(3) The LP method increases the overall weight of the sewer pipe by forming a liner inside, and the suppression of joint bending is expected to reduce the impact on manhole uplift.

(4) The SRM for existing manholes was confirmed to not only prevent damage at the connection between the manhole and sewer pipe, but also contribute to suppressing manhole uplift. However, elucidating the mechanism of uplift suppression by this method remains a subject for future study.

(5) Combining multiple methods, such as the FM method, SRM for existing manholes, and LP, can further suppress the amount of uplift.

These findings provide valuable insights for engineers and urban planners seeking to enhance the seismic resilience and durability of underground utilities in liquefaction-prone areas.

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