Toru Kouchi

8 Design Examples of Sewers Renovated by the SPR Method

This chapter introduces four design examples of sewers renovated by the SPR method using the structural analysis theories discussed in the preceding chapters. Note that the safety verification of local buckling of the bottom slab is performed based on the assumption that the invert lining is under direct groundwater pressure, which may occur when the existing cracks in the bottom slab are left untreated. The structural types of the case studies are listed in Table 8.1, which also shows the internal dimensions, overburden thicknesses and types of foundation for the selected sections of four ageing sewers.

Table 8.1: List of design examples on sewer renovation

Design example	Sewer type	Internal dimensions (mm)	Overburden thickness (m)	Foundation conditions
I	Rectangular	4,450 × 2,700	0.26–1.55	Pile foundation
II	Horseshoe-shaped	2,850 × 2,460	2.20–4.99	Pile foundation
III	Circular sewer	φ1,210	3.95–5.40	Concrete foundation
IV	Circular sewer	φ1,500	0.93–2.35	Sand-filled foundation

8.1 Example I: Rectangular Sewer

8.1.1 Internal investigation of sewer

(1) Investigation of internal cross section and damage condition

The sewer line investigated here is rectangular in cross section, and its internal dimensions and damage condition at each section are shown in Table 8.2. Based on preliminary inspections, it was decided to conduct a structural investigation on Section No. 28, where the structural deterioration was found to be most severe.

Table 8.2: Structural conditions of inspected sewer line (Example I)

Section No.	Results of inspection (measurements)			Sewer conditions
	Width (mm)	Height (mm)	Length (m)	Observed damage and judgement
19	4,410	2,670	70.30	No damage
20	4,430	2,670	60.35	No damage
21	4,400	2,650	47.05	No damage
22	4,400	2,650	63.60	No damage
23	4,430	2,660	57.70	Rebar corrosion
24	4,450	2,650	54.95	No damage
25	4,420	2,650	82.05	No damage
26	4,410	2,640	104.55	No damage
27	4,420	2,670	53.50	No damage
28	4,420	2,640	94.20	Loss of concrete cover, rebar corrosion
29	4,410	2,670	78.55	No damage
30	4,410	2,640	48.15	No damage
31	4,360	2,700	8.05	No damage

(2) Investigation items and results

The items and results of sewer investigation are shown in Table 8.3.

Table 8.3: Investigation items and results

			Results
Item			Investigation results
Cross-sectional shape			Rectangular sewer
Internal dimensions (mm)	Width		4,360–4,450
	Height		2,640–2,700
Overburden thickness (m)			0.26–1.55
Compressive strength of concrete (N/mm ²)			23.4–40.5
Member thickness (mm)	Top slab		235–500
	Sidewall	Left side	242–400
		Right side	250–435
Concrete cover (mm)	Top slab		48.0
	Sidewall	Left side	76.0
		Right side	71.0
Rebar diameter and spacing (mm)	Top slab		φ19@135
	Sidewall	Left side	φ22@333
		Right side	φ22@359
Rebar strength (N/mm ²)	Yield strength		249
	Tensile strength		414
	Based on JIS standard		SR235

8.1.2 Original design documents and determination of cross sections for structural analysis

As the design drawings used for the construction of the target sewer are available, details of the design cross section are determined based on both the results of investigation and data of the original design documents for obtaining critical conditions. Table 8.4 compares the results of structural investigation and data obtained from the original drawings and shows the cross-sectional conditions used for structural analysis.

Table 8.4: Structural details of design cross section

Item		Classification		
		Structural investigation results	As-built drawing	Design cross section
Internal dimensions (mm)		4,450 × 2,700	4,400 × 2,600	4,450 × 2,700
Overburden thickness (m)		0.26–1.55		0.26–1.55
Compressive strength of concrete (N/mm ²)		23.4		23.4
Member thickness (mm)	Top slab	235	450	235
	Sidewall	242	400	242
	Bottom slab		500	500
Concrete cover (mm)	Top slab	Inside	48.0	61.0
		Outside		61.0
	Sidewall	Inside	76.0	61.0
		Outside		76.0
	Haunch		61.0	61.0
	Bottom slab	Inside		61.0
		Outside		61.0
Rebar diameter and spacing (mm)	Top slab	Inside	φ19@135	φ22@320
		Outside		φ22@320
	Sidewall	Inside	φ22@359	φ22@320
		Outside		φ22@359
	Haunch			φ22@320
	Bottom slab	Inside		φ12@320
		Outside		φ12@320
Rebar strength (N/mm ²)	Yield strength		249	235
	Tensile strength		414	380
	Based on JIS standard		SR235	

8.1.3 General conditions for structural analysis

(1) Burial conditions, cross-sectional dimensions and rebar arrangements

Figure 8.1 shows the burial conditions of the existing sewer, its general structural dimensions, rebar arrangements and other structural details. The cross section of a sewer with standard renovation is also shown.

Figure 8.1: Cross section of sewer for structural analysis and renovation design: (a) general structural dimensions and burial conditions; (b) structural details of existing sewer; (c) cross section of sewer with standard renovation

(2) Support conditions

Based on the original design drawing as shown in Fig. 8.2, the foundation is assumed to be a fixed-bottom-slab structure.

Figure 8.2: As-built drawing (1941)

(3) Material properties

The material properties of the concrete, grouting materials, rebars and profiled steel sheets of the renovation layer are summarised in Table 8.5.

Table 8.5: Material properties

Material	Item	Specification	Unit	Remarks
Concrete members	Compressive strength	23.4	N/mm ²	Minimum test value
	Tensile strength	1.88	N/mm ²	JSCE (2013)
	Modulus of elasticity	24.70	kN/mm ²	"
	Poisson's ratio	0.2		"
	Fracture energy	83.6	N/m	"
Rebar	Yield strength	235	N/mm ²	Design value
	Modulus of elasticity	200	kN/mm ²	JSCE (2013)
Grout (Mortar No. 2)	Compressive strength	21.0	N/mm ²	Design value
	Tensile strength	1.83	N/mm ²	"
	Modulus of elasticity	6.60	kN/mm ²	"
	Poisson's ratio	0.25		"
	Fracture energy	17.6	N/m	"
Grout (Mortar No. 3)	Compressive strength	35.0	N/mm ²	Design value
	Tensile strength	2.92	N/mm ²	"
	Modulus of elasticity	22.0	kN/mm ²	"
	Poisson's ratio	0.22		"
	Fracture energy	70.8	N/m	"
Profiled steel sheet #792SU	Yield point	210	N/mm ²	Design value
	Modulus of elasticity	170	kN/mm ²	"
	Cross-sectional area	1571	mm ² /m	"

(4) Soil conditions

In view of the boring data obtained from a nearby location, soil conditions are assumed as shown in Table 8.6.

Table 8.6: Soil conditions

Boring data	Soil No.	Soil type	Depth (m)	Thickness, H_i (m)	Average N-value	Average shear wave velocity, V_{si} (m/s)	H_i/V_{si} (s)
2						
	1	Fill	4.22	4.22	2	119.72	0.035
	24						
	22	Silty sand	5.60	1.39	23	288.59	0.005
	8	Silt	6.70	1.10	8	208.44	0.005
	11						
	16	Silt	8.50	1.80	14	260.74	0.007
	42						
	45	Sand	10.80	2.30	44	363.55	0.006
	13						
	23	Silt	12.40	1.60	18	288.31	0.006
	30	Sand	13.40	1.00	30	311.91	0.003
	14						
	16						
	14						
	14						
	14						
17							
50							
50							
50							
50	Basement layer	Sand and gravel			> 50	400.0	
50							
50							

1) Static earth pressure (Fig. 8.3)

$$P_{vd} = \alpha \cdot \gamma \cdot h \text{ (kN/m}^2\text{)} \quad (8.1)$$

where P_{vd} : vertical earth pressure; α : coefficient of vertical earth pressure (= 1.0); γ : unit weight of soil (= 18.0 kN/m³); h : overburden thickness (= 0.260 m).

$$P_{hd1} = K_0 \cdot \gamma \cdot h \text{ (kN/m}^2\text{)} \quad (8.2)$$

$$P_{hd2} = K_0 \cdot \gamma \cdot (h + H_o) \text{ (kN/m}^2\text{)} \quad (8.3)$$

where P_{hd1} , P_{hd2} : horizontal earth pressure; K_0 : coefficient of horizontal earth pressure (= 0.5); H_o : outside diameter (height) of pipe (= 3.435 m).

2) Live loads (Fig. 8.4)

$$P_{vl} = \frac{Pl / 2 \times (1 + i)}{(2 \cdot h \cdot \tan \theta + b) \cdot (2 \cdot h \cdot \tan \theta + a)} \times v / b_e \text{ (kN/m}^2\text{)} \quad (8.4)$$

where P_{vl} : vertical live load; Pl : rear wheel load (= 100 kN); i : impact factor (= 0.3); a : ground contact width in the longitudinal direction (= 0.2 m); b : ground contact width in the transverse direction (= 0.5 m); θ : load distribution angle (= 45°); v : load distribution width in the longitudinal direction (= 0.720 m); b_e : effective width (= 1.010 m).

$$b_e = v + ((c - a) / 2 - h \times \tan \theta) \quad (8.5)$$

where c : distance between rear wheels (= 1.300 m).

Static earth pressure (kN/m ²)		
Vertical load	Horizontal load	
P_{vd}	P_{hd1}	P_{hd2}
4.68	2.34	33.25

Figure 8.3: Static earth pressure

Figure 8.4: Live loads

(6) Analysis model

Figures 8.5 and 8.6 show FE models for structural analysis under normal load conditions and under seismic load conditions, respectively. In view of the asymmetry of the sidewall members, a full cross-sectional model is used for structural analysis under normal loads. In the seismic performance evaluation, the ground is modelled with finite elements having sufficient coverage for pipe–soil coupled analysis.

Figure 8.5: FE model for structural analysis under normal loads

Figure 8.6: FE model for seismic performance analysis

8.1.4 Numerical results under normal load conditions

(1) Existing cross section

Figures 8.7 and 8.8 show the cracking patterns, sectional forces and structural deformations based on the FE model of the existing cross section.

Figure 8.7: Cracking pattern and structural deformation (existing cross section)

Figure 8.8: Sectional forces (existing cross section)

(2) Standard renovation cross section with SPR Mortar No. 2

Figures 8.9 and 8.10 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with SPR Mortar No. 2.

Figure 8.9: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 2)

Figure 8.10: Sectional forces (standard renovation cross section, Mortar No. 2)

(3) New cross section 1 of renovated sewer with SPR Mortar No. 2

Figures 8.11 and 8.12 show the cracking patterns, sectional forces and structural deformations based on the FE model of the new cross section 1 of renovated sewer (increasing the thickness of sidewalls by 60 mm) with SPR Mortar No. 2.

Figure 8.11: Cracking pattern and structural deformation (new cross section 1, Mortar No. 2)

Figure 8.12: Sectional forces (new cross section 1, Mortar No. 2)

(4) Standard cross section of renovated sewer with SPR Mortar No. 3

Figures 8.13 and 8.14 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard cross section of renovated sewer with SPR Mortar No. 3.

Figure 8.13: Cracking pattern and structural deformation (standard renovation, Mortar No. 3)

Figure 8.14: Sectional forces (standard renovation, Mortar No. 3)

8.1.5 Verification of safety under normal load conditions

The results of safety verification on the existing sewer and the other three renovation conditions are shown in Table 8.7. Based on these results, the following comments are made:

- In the serviceability limit state, neither the existing sewer nor the standard renovation cross section with Mortar No. 2 will meet the performance requirements because the load coefficient for cracking is less than 1.0. The standard renovation cross section with Mortar No. 3 will satisfy the performance requirements because the load coefficient for cracking is greater than 1.0.
- In the ultimate limit state, the existing sewer will not meet the performance requirements because the maximum load coefficient is less than 2.5. The standard renovation cross section with Mortar No. 2 or No. 3 will satisfy the performance requirements because the maximum load coefficient is greater than 2.5.
- If the liner thickness of the sidewalls is increased by 60 mm from the standard renovation cross section using Mortar No. 2, a renovated sewer with a new cross section 1 (internal dimensions 4,160 × 2,530 mm) will meet the performance requirements in both the serviceability limit state and the ultimate limit state, with the obtained load coefficient in each case exceeding the minimum required load coefficient.

Table 8.7: Results of safety verification based on load coefficients

Renovation condition		Parallel live load		Judgement	Remarks
Cross section	Mortar	Cracking load coefficients	Maximum load coefficients		
Existing cross section		0.10	1.09	NG	
Standard renovation	No. 2	0.90	2.83	NG	
	No. 3	1.15	3.34	OK	
New cross section 1	No. 2	1.10	3.34	OK	Increasing the thickness of sidewalls by 60 mm
Required load coefficients		> 1.0	≥ 2.5		

8.1.6 Results of seismic performance analysis

(1) Existing cross section

1) Level 1 earthquake ground motion

Figure 8.15 shows the cracking and rebar yielding of the existing cross section under Level 1 earthquake ground motion.

Figure 8.15: Cracking and rebar yielding in existing cross section (Level 1 earthquake ground motion)

2) Level 2 earthquake ground motion

Figure 8.16 shows the cracking and rebar yielding of the existing cross section under Level 2 earthquake ground motion. Table 8.8 shows the verification results under Level 2 ground motion.

Table 8.8: Verification results for existing cross section under Level 2 earthquake ground motion

Cross section		Existing cross section (4,450 × 2,680)									
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Ocean Type 2)					
Verification item		Response value	Response value/ limit value	Judge- ment	Limit value	Response value	Response value/ limit value	Judge- ment	Limit value		
Maximum compressive strain		0.0007		OK	0.0031	0.0004		OK	0.0031		
Shear force at check point (kN)	Top slab	1	79.01	1.04	NG	76.03	54.13	0.59	OK	91.24	
		2	24.79	0.27	OK	91.24	23.02	0.25	OK	91.24	
		3	87.59	1.15	NG	76.03	79.48	1.05	NG	76.03	
	Sidewall	4	72.91	0.99	OK		78.56	1.06	NG		
		5	67.38	0.91	OK		74.23	1.01	NG		
		6	73.02	0.99	OK		73.82	66.54	0.90		OK
		7	130.5	1.77	NG		63.2	0.86	OK		
		8	165.02	2.24	NG		80.69	1.09	NG		
	Bottom slab	9	163.58	1.51	NG	108.43	115.9	1.07	NG	108.43	
		10	145.86	1.42	NG	102.45	97.33	0.95	OK	102.45	
		11	50.77	0.77	OK	65.94	22.52	0.28	OK	79.13	
		12	93.18	0.91	OK	102.45	87.31	0.85	OK	102.45	
		13	110.28	1.02	NG	108.43	102.99	0.95	OK	108.43	
	Sidewall	14	83.58	1.91	NG		78.56	1.79	NG		
		15	51.72	1.18	NG		56.36	1.29	NG		
		16	43.66	1.00	NG		43.85	27.63	0.63		OK
		17	62.64	1.43	NG		40.45	0.92	OK		
		18	144.14	3.29	NG		50.29	1.15	NG		
Final judgement		NG				NG					

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Figure 8.16: Cracking and rebar yielding in existing cross section (Level 2 earthquake ground motion)

(2) Renovation with Mortar No. 2

1) New cross section 1

Numerical analyses under normal load conditions indicated that the standard renovation would not meet the performance requirements while new cross section 1 formed by increasing the sidewall thickness by 60 mm would satisfy these requirements. In the seismic performance analysis, therefore, a safety evaluation was conducted for new cross section 1. Figure 8.17 shows the cracking and rebar yielding under Level 2 earthquake ground motion, and Table 8.9 shows the verification results.

Figure 8.17: Cracking and rebar yielding in new cross section 1 with Mortar No. 2 (Level 2 earthquake ground motion)

Table 8.9: Verification results for new cross section 1 with Mortar No. 2 under Level 2 earthquake ground motion

Cross section		New cross section 1 (4,160 × 2,530)				
Renovation condition		Increasing sidewall thickness by 60 mm				
Mortar		Mortar No. 2				
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				
Verification item		Response value	Response value/limit value	Judgement	Limit value	
Maximum compressive strain		0.0011		OK	0.0031	
Shear force at check point (kN)	Top slab	1	126.10	0.33	OK	384.96
		2	55.74	0.14	OK	
		3	115.61	0.30	OK	
	Sidewall	4	92.06	0.23	OK	397.71
		5	105.79	0.27	OK	
		6	143.49	0.36	OK	
		7	210.02	0.53	OK	
		8	224.79	0.57	OK	
	Bottom slab	9	213.91	0.32	OK	663.29
		10	203.93	1.63	NG	125.10
		11	79.78	0.60	OK	132.40
		12	152.48	1.22	NG	125.10
		13	165.77	0.25	OK	663.29
	Sidewall	14	148.58	0.40	OK	367.74
		15	148.32	0.40	OK	
		16	153.59	0.42	OK	
		17	150.09	0.41	OK	
		18	146.42	0.40	OK	
Final judgement		NG				

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

2) New cross section 2

It was found that new cross section 1 would not meet the earthquake resistance requirements under Level 2 earthquake ground motion. New cross section 2, therefore, was defined by increasing the liner thickness of the bottom slab in new cross section 1 by 20 mm (internal dimensions $4,160 \times 2,510$ mm). The mortar used is Mortar No. 2. Figure 8.18 shows the cracking and rebar yielding under Level 2 earthquake ground motion in new cross section 2, and Table 8.10 shows the verification results.

Ground motion	Cracking	Rebar yielding
Inland Type 1	<p>Red line: cracking</p>	<p>Red line: rebar yielding</p>
Inland Type 2	<p>Red line: cracking</p>	<p>No rebar yielding</p>

Figure 8.18: Cracking and rebar yielding in new cross section 2 with Mortar No. 2 (Level 2 earthquake ground motion)

(3) Renovation with Mortar No. 3

1) Standard renovation cross section

Figure 8.19 shows the cracking and rebar yielding under Level 2 earthquake ground motion of a standard renovation cross section, and Table 8.11 shows the verification results.

Table 8.10: Verification results for new cross section 2 with Mortar No. 2 under Level 2 earthquake ground motion

Cross section	New cross section 2 (4,160 × 2,510)									
Renovation condition	Increasing sidewall thickness by 60 mm and bottom slab thickness by 20 mm									
Mortar	Mortar No. 2									
Input ground motion	Level 2 earthquake ground motion (Inland Type 1)					Level 2 earthquake ground motion (Inland Type 2)				
Verification item	Response value	Response value/limit value	Judge-ment	Limit value		Response value	Response value/limit value	Judge-ment	Limit value	
Maximum compressive strain	0.0010		OK	0.0031		less than 0.0031		OK	0.0031	
Shear force at check point (kN)	1	128.12	0.33	OK	384.96	96.98	0.21	OK	461.95	
	Top slab 2	56.41	0.15	OK	381.54	54.58	0.14	OK	381.54	
	3	140.14	0.36	OK	384.96	108.13	0.23	OK	461.95	
	4	89.30	0.22	OK		111.31	0.23	OK		
	5	108.22	0.27	OK		113.34	0.24	OK		
	Sidewall 6	145.91	0.37	OK	397.71	112.85	0.24	OK	477.25	
	7	206.82	0.52	OK		133.45	0.28	OK		
	8	227.14	0.57	OK		148.58	0.31	OK		
	9	211.19	0.29	OK	716.90	159.89	0.22	OK	716.90	
	10	201.57	0.92	OK	218.50	149.49	0.57	OK	262.20	
	Bottom slab 11	83.60	0.38	OK	217.71	69.09	0.32	OK	217.71	
	12	152.71	0.58	OK	262.20	157.94	0.60	OK	262.20	
	13	165.48	0.23	OK	716.90	163.74	0.23	OK	716.90	
	14	154.39	0.42	OK		168.48	0.38	OK		
	15	149.39	0.41	OK		153.21	0.35	OK		
	Sidewall 16	154.42	0.42	OK	367.74	116.31	0.26	OK	441.29	
	17	150.65	0.41	OK		93.91	0.21	OK		
	18	146.82	0.40	OK		94.01	0.21	OK		
Final judgement	OK					OK				

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Table 8.11: Verification results for standard renovation cross section with Mortar No. 3 under Level 2 earthquake ground motion

Cross section		Standard renovation cross section (4,280 × 2,530)				
Mortar		Mortar No. 3				
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				
Verification item		Response value	Response value/ limit value	Judgement	Limit value	
Maximum compressive strain		0.0012		OK	0.0031	
Shear force at check point (kN)	Top slab	1	122.63	0.28	OK	438.15
		2	63.35	0.12	OK	525.78
		3	113.14	0.26	OK	438.15
	Sidewall	4	87.73	0.30	OK	296.38
		5	101.54	0.34	OK	
		6	134.47	0.45	OK	
		7	191.57	0.65	OK	
		8	221.45	0.75	OK	
	Bottom slab	9	190.30	0.25	OK	758.83
		10	180.37	1.23	NG	146.80
		11	83.11	0.60	OK	138.14
		12	150.45	0.85	OK	176.17
		13	164.64	0.22	OK	758.83
	Sidewall	14	144.89	0.49	OK	296.38
		15	153.94	0.52	OK	
		16	158.97	0.54	OK	
		17	157.24	0.53	OK	
		18	155.37	0.52	OK	
Final judgement		NG				

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Figure 8.19: Cracking and rebar yielding in standard renovation cross section with Mortar No. 3 (Level 2 earthquake ground motion)

2) New cross section 3

It was found that a standard renovation cross section would not meet the earthquake resistance requirements under Level 2 earthquake ground motion. New cross section 3, therefore, was defined by raising the centre of the liner by 10 mm, i.e., increasing the liner thickness of the bottom slab by 10 mm and reducing the liner thickness of the top plate by 10 mm (internal dimensions $4,280 \times 2,520$ mm). The mortar used is Mortar No. 3. Figure 8.20 shows the cracking and rebar yielding under Level 2 earthquake ground motion of new cross section 3, and Table 8.12 shows the verification results.

Figure 8.20: Cracking and rebar yielding in new cross section 3 with Mortar No. 3 (Level 2 earthquake ground motion)

Table 8.12: Verification results for new cross section 3 with Mortar No. 3 under Level 2 earthquake ground motion

Cross section	New cross section 3 (4,280 × 2,520)									
Renovation condition	Increasing bottom slab thickness by 10 mm, and reducing top plate thickness by 10 mm									
Mortar	Mortar No. 3									
Input ground motion	Level 2 earthquake ground motion (Inland Type 1)					Level 2 earthquake ground motion (Inland Type 2)				
Verification item	Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value		
Maximum compressive strain	0.0011		OK	0.0031	0.0001		OK	0.0031		
Shear force at check point (kN)	Top slab	1	122.47	0.30	OK	411.97	99.50	0.20	OK	494.36
		2	61.58	0.12	OK	494.36	56.81	0.11	OK	494.36
		3	160.66	0.39	OK	411.97	111.08	0.22	OK	494.36
	Sidewall	4	86.40	0.29	OK	296.38	113.47	0.32	OK	355.66
		5	100.02	0.34	OK		114.81	0.32	OK	
		6	133.12	0.45	OK		113.71	0.32	OK	
		7	191.54	0.65	OK		132.19	0.37	OK	
		8	216.88	0.73	OK		147.94	0.42	OK	
	Bottom slab	9	189.82	0.24	OK	790.25	157.13	0.20	OK	790.25
		10	179.30	0.83	OK	215.24	146.42	0.57	OK	258.29
		11	86.08	0.41	OK	210.15	68.76	0.33	OK	210.15
		12	151.17	0.59	OK	258.29	154.10	0.60	OK	258.29
		13	165.76	0.21	OK	790.25	160.63	0.20	OK	790.25
	Sidewall	14	146.86	0.50	OK	296.38	168.17	0.57	OK	296.38
		15	152.90	0.52	OK		152.46	0.51	OK	
		16	158.75	0.54	OK		114.74	0.39	OK	
		17	156.02	0.53	OK		95.23	0.32	OK	
		18	154.20	0.52	OK		95.87	0.32	OK	
Final judgement	OK				OK					

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

8.1.7 Verification of safety under earthquake loading

The results of seismic safety verifications on the existing sewer and the other four types of renovation conditions are shown in Table 8.13. Based on these results, the following comments are made:

- The verification results indicate that under Level 1 earthquake ground motion, the existing sewer meets the earthquake resistance requirements.
- The verification results indicate that under Level 2 earthquake ground motion, the existing sewer does not meet the earthquake resistance requirements, but new cross section 2 with Mortar No. 2 and new cross section 3 with Mortar No. 3 meet the earthquake resistance requirements.
- With new cross section 3 and Mortar No. 3, the load coefficient for cracking is 1.12 and the maximum load coefficient is 3.30, satisfying the performance requirements under normal load conditions.

Table 8.13: Results of safety verification under earthquake loading

Renovation condition		Level 1 earthquake ground motion	Level 2 earthquake ground motion		Remarks
Cross section	Mortar		Ultimate displacement	Shear force	Judgment
Existing cross section		OK	OK	NG	NG
Standard renovation	No. 3		OK	NG	NG
New cross section 1	No. 2		OK	NG	NG
New cross section 2	No. 2		OK	OK	OK
New cross section 3	No. 3		OK	OK	OK

Note: Ultimate displacement under Level 2 earthquake ground motion is verified by checking the maximum compressive strain.

8.1.8 Safety verification of local buckling of the bottom slab

The possibility of local buckling of the renovation layer at the bottom slab under groundwater pressure is checked for three renovation conditions: the standard

renovation cross section with Mortar No. 2, new cross section 2 with Mortar No. 2 and new cross section 3 with Mortar No. 3. The buckling equation employed is

$$P_{cr} = \frac{1.28E}{(1-\nu^2)} \left(\frac{I}{R^3} \right)^{3/5} \left(\frac{\pi A}{L} \right)^{2/5} \quad (\text{N/mm}^2) \quad (8.6)$$

where P_{cr} = buckling strength; I = moment of inertia of area; R = invert radius of renovation layer; L = invert length of renovation layer; A = cross sectional area of renovation layer; E = modulus of elasticity; ν = Poisson's ratio. Note that Eq. (8.6) was derived in Section 5.4.

Buckling analyses on the three renovation conditions show that, while the possibility of local buckling exists for the case of standard renovation with Mortar No. 2, the other two renovation conditions have sufficient buckling strength against the maximum groundwater pressure. Details of the verification study on local buckling are presented in Table 8.14.

Table 8.14: Safety verification of local buckling of bottom slab

Item	Variable	Unit	Renovation condition		
			Standard renova- tion cross section	New cross section 2	New cross section 3
			Mortar No. 2	Mortar No. 2	Mortar No. 3
Maximum overburden thickness	h	m	1.550		
Height of sewer	H_o	m	3.435		
Poisson's ratio of liner	ν		0.30		
Liner thickness at bottom slab	t	mm	31.7	51.7	41.7
Invert radius	R	mm	9,300		
Invert length of liner	L	mm	3,300	3,180	3,300
Moment of inertia of area	I	mm ³ / mm	2.655	11.516	6.043
Cross-sectional area of liner	A	mm ² / mm	31.7	51.7	41.7
Equivalent stiffness of liner	E	N/mm ²	12.71×10^3	10.35×10^3	21.25×10^3
Buckling strength	P_{cr}	N/mm ²	0.036	0.087	0.110
Maximum groundwater pressure	P_w	N/mm ²	0.049		
Safety factor	γ		1.5		
Safety verification			$P_{cr} < \gamma P_w$	$P_{cr} > \gamma P_w$	$P_{cr} > \gamma P_w$
Judgement			NG	OK	OK

8.1.9 Determination of renovation methods

(1) Structural strength

Though the existing sewer can withstand a Level 1 earthquake force, it is not strong enough to withstand a Level 2 earthquake ground motion, and it fails to meet the performance requirements under normal load conditions. Therefore, structural renovation has to be performed on this sewer line. In cases where Mortar No. 2 is used, the required structural strength is achieved by increasing both the sidewall thickness by 60 mm and the bottom slab thickness by 20 mm from the standard renovation cross section. In cases where Mortar No. 3 is used, the required structural strength is achieved by reducing the top plate thickness by 10 mm and increasing the bottom slab thickness by 10 mm from the standard renovation cross section.

(2) Achieving the required discharge capacity

The required discharge capacity of the renovated sewer is studied by calculating the flow ratio based on the following equation:

$$\text{Flow ratio} = \text{Discharge capacity (m}^3/\text{s)} / \text{Total flow (m}^3/\text{s)} \quad (8.7)$$

where discharge capacity = $A \cdot v$; A = cross-sectional area (m^2); v = flow velocity (m/s). The flow velocity is defined as $v = 1/n \cdot R^{2/3} \cdot I^{1/2}$, where n = roughness coefficient; R = wetted perimeter (m); I = slope. Note that for the existing sewer of reinforced concrete $n = 0.013$, and for the renovated sewer with the PVC liner $n = 0.010$. The lower roughness coefficient is partially or totally compensating for the reduction in the cross-sectional area of a renovated sewer. The discharge capacity at each section of the renovated sewer is calculated and shown in Table 8.15.

(3) Conclusions

Based on the various analysis results discussed above, sewer renovation will be carried out for this sewer line to strengthen its earthquake resistance, and to mitigate flooding damage by keeping its discharge capacity adequate. Since this sewer line contains a section where the flow ratio of the existing sewer is lower than 1.0, it is necessary to maximise the cross section of the sewer. Therefore, the renovation methods are determined based on the structural details of new cross section 3 with Mortar No. 3. The renovation plan for each section of this sewer line is listed in Table 8.15.

Table 8.15: List of renovation plans (Example I)

Section No.		19	20	21	22	23	24	25
Sewer length (m)		70.30	60.35	47.05	63.60	57.70	54.95	82.05
Dimensions	Existing sewer	4,410 × 2,670	4,430 × 2,670	4,400 × 2,650	4,400 × 2,650	4,430 × 2,660	4,450 × 2,650	4,420 × 2,650
	After renovation	4,200 × 2,420	4,200 × 2,420	4,200 × 2,420	4,200 × 2,420	4,200 × 2,420	4,200 × 2,420	4,200 × 2,420
Slope (‰)	Existing sewer	1.7	1.8	0.9	2.4	2.2	1.0	1.7
	After renovation	1.7	1.4	1.4	1.9	1.9	1.9	1.9
Flow ratio	Existing sewer	1.16	1.22	0.84	1.34	1.33	0.84	1.07
	After renovation	1.23	1.12	1.11	1.30	1.30	1.21	1.11
Section No.		26	27	28	29	30	31	
Sewer length (m)		104.55	53.50	94.20	78.55	48.15	8.05	
Dimensions	Existing sewer	4,410 × 2,640	4,420 × 2,670	4,420 × 2,640	4,410 × 2,670	4,410 × 2,640	4,360 × 2,700	
	After renovation	4,200 × 2,420	4,200 × 2,420	4,230 × 2,420	4,210 × 2,440	4,190 × 2,400	4,190 × 2,400	
Slope (‰)	Existing sewer	1.6	1.7	1.6	1.9	1.2	3.5	
	After renovation	1.6	1.6	1.6	1.6	1.6	3.5	
Flow ratio	Existing sewer	1.04	1.07	0.99	1.06	0.84	1.77	
	After renovation	1.12	1.09	1.09	1.07	1.04	1.87	

8.2 Example II: Horseshoe-shaped Sewer

8.2.1 Internal investigation of sewer

(1) Investigation of internal cross section and damage condition

This sewer is horseshoe-shaped in cross section, and its internal dimensions and damage condition at each section are shown in Table 8.16. Based on preliminary inspections, it was decided to conduct a structural investigation of Section No. 16, where the structural deterioration was found to be most severe.

Table 8.16: Structural conditions of inspected sewer line (Example II)

Section No.	Results of inspection (measurements)			Sewer conditions
	Width (mm)	Height (mm)	Length (m)	
10	2,820	2,140	98.90	Cracks, groundwater infiltration, fracture
11	2,850	2,160	61.30	Cracks, groundwater infiltration
12	2,800	2,170	104.70	Cracks, groundwater infiltration
13	2,730	2,460	21.90	No damage
14	2,720	2,450	64.90	Cracks, groundwater infiltration
15	2,720	2,450	59.90	Groundwater infiltration, deposits
16	2,730	2,440	102.35	Cracks, groundwater infiltration, surface deterioration, rebar corrosion
17	2,730	2,470	18.50	No damage

(2) Investigation items and results

The items and results of sewer investigation are shown in Table 8.17.

Table 8.17: Investigation items and results

			Results
Item			Investigation results
Cross-sectional shape			Horseshoe-shaped sewer
Internal dimensions (mm)	Width		2,720–2,850
	Height		2,140–2,460
Overburden thickness (m)			2.20–4.99
Compressive strength of concrete (N/mm ²)			24.1–30.6
Member thickness (mm)	Top slab		244
	Sidewall	Left side	400
		Right side	435
Concrete cover (mm)	Top slab		21.0
	Sidewall	Left side	21.0
		Right side	22.0
Rebar diameter and spacing (mm)	Top slab		φ11.8@168
	Sidewall	Left side	φ13.2@160
		Right side	φ13.2@178
Rebar strength (N/mm ²)	Yield strength		262
	Tensile strength		354
	Based on JIS standard		None

8.2.2 Original design documents and determination of cross sections for structural analysis

As the design drawings used for the construction of the target sewer are available, details of the design cross section are determined based on both the results of investigation and data of the original design documents for obtaining the critical conditions. Table 8.18 compares the results of structural investigation and data obtained from the original drawings and shows the cross-sectional conditions used for structural analysis.

Table 8.18: Structural details of design cross section

				Classification		
Item				Structural investi-	As-built	Design cross
				gation results	drawing	section
Internal dimensions (mm)				2,850 × 2,460	2,730 × 2,450	2,850 × 2,460
Overburden thickness (m)				2.20–4.99		2.20–4.99
Compressive strength of concrete (N/mm ²)				24.1		24.1
Member thickness (mm)	Top slab			244	242	242
	Sidewall			400	530	400
	Bottom slab				364	364
Concrete cover (mm)	Top slab	Inside	21.0		46.0	46.0
		Outside			46.0	46.0
	Sidewall	Inside	21.0		46.0	46.0
		Outside			46.0	46.0
	Bottom slab	Inside			46.0	46.0
		Outside			55.0	55.0
Rebar diameter and spacing (mm)	Top slab	Inside	φ11.8@168		φ12.7@171	φ11.8@178
		Outside			φ12.7@171	φ12.7@178
	Sidewall	Inside	φ13.2@178		φ12.7@171	φ11.8@178
		Outside			φ12.7@171	φ12.7@178
	Bottom slab	Inside			φ12.7@171	φ12.7@171
		Outside			φ12.7@171	φ12.7@171
Rebar strength (N/mm ²)	Yield strength		262			262
	Tensile strength		354			354
	Based on JIS standard		None			None

Figure 8.21 shows the burial conditions of the existing sewer, its general structural dimensions, rebar arrangements and other structural details. The cross section of a sewer with standard renovation is also shown.

Figure 8.21: Cross section of sewer for structural analysis and renovation design: (a) general structural dimensions and burial conditions; (b) structural details of existing sewer; (c) cross section of sewer with standard renovation

Based on the original design drawing as shown in Fig. 8.22, the foundation is assumed to be a fixed-bottom-slab structure.

Figure 8.22: As-built drawing (1926)

(3) Material properties

Material properties of concrete, grouting materials, rebars and profiled steel sheets of the renovation layer are summarised in Table 8.19.

Table 8.19: Materials properties

Material	Item	Specification	Unit	Remarks
Concrete members	Compressive strength	24.1	N/mm ²	Minimum test value
	Tensile strength	1.92	N/mm ²	JSCE (2013)
	Modulus of elasticity	25.1	kN/mm ²	"
	Poisson's ratio	0.2		"
	Fracture energy	84.5	N/m	"
Rebar	Yield strength	262	N/mm ²	Test value
	Modulus of elasticity	200	kN/mm ²	JSCE (2013)
Grout (Mortar No. 2)	Compressive strength	21.0	N/mm ²	Design value
	Tensile strength	1.83	N/mm ²	"
	Modulus of elasticity	6.60	kN/mm ²	"
	Poisson's ratio	0.25		"
Grout (Mortar No. 3)	Fracture energy	17.6	N/m	"
	Compressive strength	35.0	N/mm ²	Design value
	Tensile strength	2.92	N/mm ²	"
	Modulus of elasticity	22.0	kN/mm ²	"
	Poisson's ratio	0.22		"
Profiled steel sheet #792SU	Fracture energy	70.8	N/m	"
	Yield strength	210	N/mm ²	Design value
	Modulus of elasticity	170	kN/mm ²	"
	Cross-sectional area	1571	mm ² /m	"

(4) Soil conditions

In view of the boring data obtained from a nearby location, soil conditions are assumed as shown in Table 8.20.

Table 8.20: Soil conditions

Boring data	Soil No.	Soil type	Depth (m)	Thickness, H_i (m)	Average N-value	Average shear wave velocity, V_{si} (m/s)	H_i/V_{si} (s)	
	2	1	Surface soil	2.90	2	108.64	0.027	
	10	2	Sand	4.10	10	200.99	0.006	
	3	3	Silt	7.90	2	119.72	0.032	
	1	4	Sand	8.60	0.70	2	105.58	0.007
	1	5	Sand	9.60	1.00	17	248.52	0.004
	2	6	Sand	10.70	1.10	43	360.22	0.003
	17	7	Sand	12.80	2.10	21	270.44	0.008
	43	8	Sandy silt	13.30	0.50	8	208.44	0.002
	21	9	Sandy silt	14.80	1.50	12	245.15	0.006
	21	10	Silt	25.10	10.30	5	172.72	0.060
	8	11	Sandy silt	28.50	3.40	9	218.50	0.016
	12	12	Loamy clay	32.90	4.40	17	281.79	0.016
	18	13	Sand	34.20	1.30	45	348.01	0.004
	19	Basement layer	Sand and gravel					
	45							
	50							
	50							
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Evaluation of ground property: $T_g = 4 \sum_{i=1}^n \frac{H_i}{V_{si}} = 0.300$ (s), Class II

Classification of ground: $T_g < 0.2$, Class I; $0.2 \leq T_g < 0.6$, Class II; $0.6 \leq T_g$, Class III

(5) Load conditions

Since the overburden thickness along this sewer line exceeds 4 m in some sections, the maximum overburden thickness (4.99 m) is used to define load conditions. As the overburden thickness is greater than 4 m, a live load of 10 kN/m² is applied uniformly.

1) Static earth pressure

Applied static earth pressures are shown in Fig. 8.23. For details of earth pressure computation, refer to Example I. Note that the coefficient of horizontal earth pressure, K_o , is 0.3 for the present case.

2) Live loads

Applied live loads are shown in Fig. 8.24. Note that the coefficient of horizontal earth pressure, K_o , is 0.3 for the present case.

Figure 8.23: Static earth pressure

Figure 8.24: Live loads

(6) Analysis model

Figures 8.25 and 8.26 show FE models for structural analysis under normal load conditions and under seismic load conditions, respectively. In view of the structural symmetry of the cross section, a half cross-sectional model is used for structural analysis under normal loads. In the seismic performance evaluation, the ground is modelled with finite elements having sufficient coverage for pipe–soil coupled analysis.

Figure 8.25: FE model for structural analysis under normal loads

Figure 8.26: FE model for seismic performance analysis

8.2.4 Numerical results under normal load conditions

(1) Existing cross section

Figures 8.27 and 8.28 show the cracking patterns, sectional forces and structural deformations based on the FE model of the existing cross section.

Figure 8.27: Cracking pattern and structural deformation (existing cross section)

Figure 8.28: Sectional forces (existing cross section)

(2) Standard renovation cross section with Mortar No. 2

Figures 8.29 and 8.30 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with Mortar No. 2.

Figure 8.29: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 2)

Figure 8.30: Sectional forces (standard renovation cross section, Mortar No. 2)

(3) Standard renovation cross section with Mortar No. 3

Figures 8.31 and 8.32 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with Mortar No. 3.

Figure 8.31: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 3)

Figure 8.32: Sectional forces (standard renovation cross section, Mortar No. 3)

8.2.5 Verification of safety under normal load conditions

The results of safety verification on the existing sewer and the other two renovation conditions are shown in Table 8.21. Based on these results, the following comments are made:

- In the serviceability limit state, the existing sewer will not meet the performance requirements because the load coefficient for cracking is less than 1.0. The standard renovation cross section with Mortar No. 2 or No. 3 will satisfy the performance requirements because the load coefficient for cracking is greater than 1.0.
- In the ultimate limit state, the existing sewer will meet the performance requirements because its maximum load coefficient is greater than 2.5. The standard renovation cross section with Mortar No. 2 or No. 3 will also satisfy the performance requirements because the maximum load coefficient exceeds 2.5.

Table 8.21: Results of safety verification based on load coefficients

Renovation condition		Parallel live load (10 kN/m ²)		Judgement	Remarks
Cross section	Mortar	Cracking load coefficients	Maximum load coefficients		
Existing cross section		0.30	3.09	NG	
Standard renovation	No. 2	2.10	8.08	OK	
	No. 3	3.30	14.07	OK	
Required load coefficients		> 1.0	≥ 2.5		

8.2.6 Results of seismic performance analysis

(1) Existing cross section

1) Level 1 earthquake ground motion

Figure 8.33 shows the cracking and rebar yielding of the existing cross section under Level 1 earthquake ground motion.

Figure 8.33: Cracking and rebar yielding in existing cross section (Level 1 earthquake ground motion)

2) Level 2 earthquake ground motion

Figure 8.34 shows the cracking and rebar yielding of the existing cross section under Level 2 earthquake ground motion. Table 8.22 shows the verification results under Level 2 ground motion.

Figure 8.34: Cracking and rebar yielding in existing cross section (Level 2 earthquake ground motion)

Table 8.22: Verification results for existing cross section under Level 2 earthquake ground motion

Cross section		Existing cross section (2,850 × 2,460)							
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Ocean Type 2)			
Verification item		Response				Response			
		Responsevalue/ value	limit value	Judge- ment	Limit value	Responsevalue/ value	limit value	Judge- ment	Limit value
Maximum compressive strain		0.0005		OK	0.0031	Less than 0.0031		OK	0.0031
Shear force at check point (kN)	Top slab	1	78.49	1.32	NG	59.46	54.46	0.76	OK
		2	78.14	1.31	NG		62.35	0.87	OK
	Right arch	3	67.48	0.97	OK	69.47	62.08	0.89	OK
		4	93.21	1.34	NG		81.03	1.17	NG
	Right sidewall	5	140.89	1.59	NG	88.65	122.94	1.16	NG
		6	170.03	1.92	NG		81.50	0.77	OK
		7	241.97	2.73	NG		152.28	1.43	NG
		8	290.67	2.80	NG	103.74	214.04	1.72	NG
		9	244.61	2.62	NG	93.53	162.93	1.74	NG
	Bottom slab	10	183.19	2.08	NG	88.17	106.93	1.01	NG
		11	204.17	2.18	NG	93.53	186.02	1.66	NG
		12	249.49	2.40	NG	103.74	232.34	1.87	NG
	Left sidewall	13	197.6	2.23	NG	88.65	172.18	1.62	NG
		14	151.00	1.70	NG		101.89	0.96	OK
		15	194.36	2.19	NG		103.10	0.97	OK
	Right arch	16	149.01	2.14	NG	69.47	67.43	0.97	OK
		17	64.68	0.93	OK		49.26	0.71	OK
	Top slab	18	84.60	1.42	NG	59.46	45.17	0.76	OK
Final judgement		NG				NG			

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

(2) Renovation with Mortar No. 2

1) Standard renovation cross section

Figure 8.35 shows the cracking and rebar yielding of the standard renovation cross section with Mortar No. 2 under Level 2 earthquake ground motion. Table 8.23 shows the verification results.

Figure 8.35: Cracking and rebar yielding in standard renovation cross section with Mortar No. 2 (Level 2 earthquake ground motion)

2) New cross section 1

It was found that the standard renovation cross section with Mortar No. 2 would not meet the earthquake resistance requirements under Level 2 earthquake ground motion. New cross section 1, therefore, was defined by keeping the inner diameter of the standard renovation cross section and raising the centre of the renovated sewer by 70 mm, thus increasing the liner thickness of the bottom slab by 70 mm and reducing the liner thickness of the top plate by 70 mm (internal dimensions $2,680 \times 2,290$ mm). Figure 8.36 shows the cracking and rebar yielding of new cross section 1 under Level 2 earthquake ground motion. Table 8.24 shows the verification results.

Table 8.23: Verification results for standard renovation cross section with Mortar No. 2 under Level 2 earthquake ground motion

Cross section		Standard renovation cross section (2,680 × 2,290)				
Mortar		Mortar No. 2				
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				
Verification item		Response value	Response value/limit value	Judgement	Limit value	
Maximum compressive strain		0.0003		OK	0.0031	
Shear force at check point (kN)	Top slab	1	115.88	0.26	OK	442.07
		2	98.58	0.22	OK	
	Right arch	3	79.14	0.21	OK	377.73
		4	122.37	0.32	OK	
	Right sidewall	5	153.12	0.55	OK	278.52
		6	205.54	0.72	OK	
		7	275.00	0.57	OK	482.21
		8	313.06	0.74	OK	
		9	299.74	2.17	NG	137.92
		Bottom slab	10	235.17	1.48	
			11	238.62	1.73	NG
			12	257.29	0.61	OK
			13	214.12	0.37	OK
		Left sidewall	14	199.81	0.59	OK
			15	233.07	0.70	OK
		Left arch	16	149.01	0.39	OK
			17	95.95	0.25	OK
		Top slab	18	123.82	0.28	OK
Final judgement		NG				

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Table 8.24: Verification results for new cross section 1 with Mortar No. 2 under Level 2 earthquake ground motion

Cross section	New cross section 1 (2,680 × 2,290)									
Renovation conditions	Increasing bottom slab thickness by 70 mm, and reducing top plate thickness by 70 mm									
Mortar	Mortar No. 2									
Input ground motion	Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Inland Type 2)					
Verification item	Response				Response					
	Response value	value/limit value	Judge-ment	Limit value	Response value	value/limit value	Judge-ment	Limit value		
Maximum compressive strain	0.0004		OK	0.0031	0.0003		OK	0.0031		
Shear force at check point (kN)	Top slab	1	95.71	0.38	OK	254.43	105.33	0.41	OK	254.43
		2	84.49	0.33	OK		108.54	0.43	OK	
	Right arch	3	66.48	0.30	OK	221.36	73.37	0.33	OK	221.36
		4	112.50	0.51	OK		128.43	0.58	OK	
	Sidewall	5	155.13	0.56	OK	278.52	214.13	0.64	OK	334.22
		6	211.45	0.74	OK	284.07	176.19	0.53	OK	340.89
		7	280.18	0.57	OK	489.43	247.16	0.74	OK	587.32
	Bottom slab	8	324.16	0.56	OK	581.09	302.04	0.43	OK	697.31
		9	315.86	0.98	OK	320.70	274.79	0.86	OK	320.70
		10	255.78	0.68	OK	378.41	241.61	0.64	OK	378.41
	Left sidewall	11	235.60	0.73	OK	320.70	310.44	0.97	OK	320.70
		12	269.77	0.46	OK	581.09	323.78	0.56	OK	581.09
		13	212.48	0.36	OK	587.32	285.50	0.58	OK	489.43
	Left arch	14	183.15	0.54	OK	340.89	215.26	0.44	OK	284.07
		15	220.47	0.66	OK	334.22	187.16	0.38	OK	334.22
	Top slab	16	146.55	0.66	OK	221.36	125.41	0.57	OK	221.36
		17	76.81	0.35	OK		67.58	0.31	OK	
	Top slab	18	103.70	0.49	OK	254.43	91.82	0.43	OK	254.43
Final judgement	OK				OK					

Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Figure 8.36: Cracking and rebar yielding in new cross section 1 with Mortar No. 2 (Level 2 earthquake ground motion)

(3) Renovation with Mortar No. 3

New renovation cross section 2: The response value of the standard renovation cross section with Mortar No. 2 exceeded the limit value by a factor of up to 2.17 times under Level 2 earthquake force. It was judged that the standard renovation cross section would not meet the performance requirements even if Mortar No. 3 was used. New cross section 2, therefore, was defined by keeping the inner diameter of the standard renovation cross section and raising the centre of the renovated sewer by 50 mm, thus increasing the liner thickness of the bottom slab by 50 mm and reducing the liner thickness of the top plate by 50 mm (internal dimensions 2,680 × 2,290 mm). Figure 8.37 shows the cracking and rebar yielding of new cross section 2 under Level 2 earthquake ground motion. Table 8.25 shows the verification results.

Figure 8.37: Cracking and rebar yielding in new cross section 2 with Mortar No. 3 (Level 2 earthquake ground motion)

8.2.7 Verification of safety under earthquake loading

The results of seismic safety verifications on the existing sewer and the other four types of renovation conditions are shown in Table 8.26. Based on these results, the following comments are made:

- The verification results indicate that under Level 1 earthquake ground motion, the existing sewer meets the earthquake resistance requirements.
- The verification results indicate that under Level 2 earthquake ground motion, the existing sewer does not meet the earthquake resistance requirements, but new cross section 1 with Mortar No. 2 and new cross section 2 with Mortar No. 3 meet the earthquake resistance requirements.
- With new cross section 1 and Mortar No. 2, the load coefficient for cracking is 1.50 and the maximum load coefficient is 5.75, satisfying the performance requirements under normal load conditions.
- With new cross section 2 and Mortar No. 3, the load coefficient for cracking is 2.30 and the maximum load coefficient is 8.82, satisfying the performance requirements under normal load conditions.

Table 8.25: Verification results for new cross section 2 with Mortar No. 3 under Level 2 earthquake ground motion

Cross section	New cross section 2 (2,680 × 2,290)									
Renovation conditions	Increasing bottom slab thickness by 50 mm, and reducing top plate thickness by 50 mm									
Mortar	Mortar No. 3									
Input ground motion	Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Inland Type 2)					
Verification item	Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value		
Maximum compressive strain	0.0003		OK	0.0031	0.0003		OK	0.0031		
Shear force at check point (kN)	Top slab	1	119.74	0.40	OK	300.44	128.87	0.36	OK	360.52
		2	92.75	0.31	OK		133.10	0.37	OK	
	Right arch	3	70.66	0.24	OK	299.89	95.35	0.32	OK	299.89
		4	148.21	0.49	OK		145.32	0.48	OK	
	Right sidewall	5	177.03	0.57	OK	311.21	212.40	0.57	OK	373.45
		6	233.24	0.75	OK		178.14	0.48	OK	
		7	295.59	0.95	OK		249.19	0.67	OK	
	Bottom slab	8	317.05	0.52	OK	610.92	298.12	0.41	OK	733.10
		9	304.05	0.99	OK	307.45	270.95	0.88	OK	307.45
		10	250.93	0.69	OK	362.51	234.85	0.65	OK	362.51
		11	232.23	0.76	OK	307.45	301.16	0.98	OK	307.45
		12	266.14	0.44	OK	610.92	319.01	0.44	OK	733.10
	Left sidewall	13	212.98	0.57	OK	373.45	294.20	0.95	OK	311.21
		14	181.33	0.49	OK		228.77	0.74	OK	
		15	216.40	0.58	OK		187.21	0.60	OK	
	Left arch	16	141.70	0.47	OK	299.89	122.79	0.41	OK	299.89
		17	100.85	0.34	OK		74.90	0.25	OK	
	Top slab	18	130.06	0.36	OK	360.52	105.07	0.35	OK	300.44
Final judgement	OK				OK					

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Table 8.26: Results of safety verification under earthquake loading

Renovation condition		Level 1 earthquake ground motion	Level 2 earthquake ground motion		Remarks
Cross section	Mortar		Ultimate displace- ment	Shear force Judge-ment	
Existing cross section		OK	OK	NG	NG
Standard renovation cross section	No. 2		OK	NG	NG
New cross section 1	No. 2		OK	OK	OK
New cross section 2	No. 3		OK	OK	OK

Note: Ultimate displacement under Level 2 earthquake ground motion is verified by checking the maximum compressive strain.

8.2.8 Safety verification of local buckling of the bottom slab

The possibility of local buckling of the renovation layer at the bottom slab under groundwater pressure is checked for three renovation conditions: the standard renovation cross section with Mortar No. 2, new cross section 1 with Mortar No. 2 and new cross section 2 with Mortar No. 3. For details of buckling strength computation, refer to Example I.

Buckling analyses on the three renovation conditions show that, while the possibility of local buckling exists for the case of standard renovation with Mortar No. 2, the other two renovation conditions have sufficient buckling strength against the maximum groundwater pressure. Details of the verification study on local buckling are presented in Table 8.27.

Table 8.27: Safety verification of local buckling of bottom slab

Item	Variable	Unit	Renovation condition		
			Standard reno- vation cross section	New cross section 1	New cross section 2
			Mortar No. 2	Mortar No. 2	Mortar No. 3
Maximum overburden thickness	h	m	4.990		
Height of sewer	H_o	m	3.066		
Poisson's ratio of liner	ν		0.30		
Liner thickness at bottom slab	t	mm	31.7	101.7	81.7
Invert radius	R	mm	7,410		
Invert length of liner	L	mm	1,440		
Moment of inertia of area	I	mm ³ /mm	2.655	87.656	45.445
Cross-sectional area of liner	A	mm ² /mm	31.7	101.7	81.7
Equivalent stiffness of liner	E	N/mm ²	12.71×10^3	8.51×10^3	21.62×10^3
Buckling strength	P_{cr}	N/mm ²	0.075	0.655	1.028
Maximum groundwater pressure	P_w	N/mm ²	0.079		
Safety factor	γ		1.5		
Safety verification			$P_{cr} < \gamma P_w$	$P_{cr} > \gamma P_w$	$P_{cr} > \gamma P_w$
Judgement			NG	OK	OK

8.2.9 Determination of renovation methods

(1) Structural strength

Though the existing sewer can withstand Level 1 earthquake force, it is not strong enough to withstand Level 2 earthquake ground motion, and it fails to meet the performance requirements under normal load conditions. Therefore, structural renovation has to be performed on this sewer line. In cases where Mortar No. 2 is used, the required structural strength is achieved by increasing the bottom slab thickness by 70 mm and reducing the top plate thickness by 70 mm from the standard renovation cross section. In cases where Mortar No. 3 is used, the required structural strength is achieved by increasing the bottom slab thickness by 50 mm and reducing the top plate thickness by 50 mm from the standard renovation cross section.

(2) Achieving the required discharge capacity

The discharge capacity at each section of the renovated sewer is calculated and shown in Table 8.28. Due to the significant reduction of the cross-sectional area in an effort to eliminate the adverse slope in this sewer line, the flow ratios at most of the sections are less than 1.0. However, with the fast reconstruction of the sewer system in this region, the future drainage area of this sewer line will be much reduced and the corresponding flow ratios will then become adequate, as shown in the same table. For details of flow ratio computation, refer to Example I.

Table 8.28: List of renovation plans (Example II)

Sewer No.		10	11	12	13	14	15	16	17
Sewer length (m)		98.90	61.30	104.70	21.90	64.90	59.90	102.35	18.50
Shape	Existing sewer	2,820 × 2,140	2,850 × 2,160	2,800 × 2,170	2,730 × 2,460	2,720 × 2,450	2,720 × 2,450	2,730 × 2,440	2,730 × 2,470
	After renovation	2,630 × 1,670	2,660 × 1,810	2,600 × 1,730	2,560 × 2,030	2,540 × 2,070	2,540 × 2,160	2,550 × 2,110	2,550 × 2,170
Slope (‰)	Existing sewer	-1.8	0.8	1.2	-3.0	-1.0	1.1	0.6	1.6
	After renovation	0.2	0.2	0.3	0.3	0.3	1.1	0.6	1.6
Flow ratio	Existing sewer		1.18	1.40			1.32	0.93	1.44
	After renovation	0.49	0.53	0.58	0.65	0.64	1.31	0.90	1.42
	Renovated sewer (based on future drainage area)	1.54	1.38	1.40	1.26	1.20	2.40	1.56	2.26

(3) Conclusion

Based on the various analysis results discussed above, sewer renovation will be carried out for this sewer line to strengthen its earthquake resistance, and to mitigate flooding damage by keeping its discharge capacity adequate. Since the existing sewer line contains adverse slope sections, the renovation approach adopted is to use new cross section 2 with Mortar No. 3 because that allows a more flexible adjustment of bottom slab thickness. The renovation plan for each section of this sewer line is listed in Table 8.28.

8.3 Example III: Circular Sewer (Concrete Foundation)

8.3.1 Internal investigation of sewer

(1) Investigation of internal cross section and damage condition

The sewer line investigated here is a circular pipe, and its internal diameter and damage condition at each section are shown in Table 8.29. Based on preliminary inspections, it was decided to conduct a structural investigation on Section No. 8, where the structural deterioration was found to be most severe.

Table 8.29: Structural conditions of inspected sewer line (Example III)

Section No.	Results of inspection (measurements)		Sewer conditions
	Diameter (mm)	Length (m)	Observed damage and judgement
4	φ1,210	10.39	No damage
5	φ1,210	7.39	No damage
6	φ1,210	24.21	No damage
7	φ1,210	60.63	Surface deterioration
8	φ1,210	80.36	Surface deterioration
9	φ1,210	37.36	Surface deterioration
10	φ1,210	11.30	No damage

(2) Investigation items and results

The items and results of sewer investigation are shown in Table 8.30.

Table 8.30: Investigation items and results

		Results
Item		Investigation results
Cross-sectional shape		Circular
Internal dimensions	Diameter	φ1,210
Overburden thickness (m)		3.95–5.40
Compressive strength of concrete (N/mm ²)		21.2–37.5
Member thickness (mm)		96.0
Surface corrosion thickness (mm)		10.0
Concrete cover (mm)		40.0
		* Including surface corrosion thickness
Rebar diameter and spacing (mm)		φ7.0@81
Rebar strength	Yield strength	
(N/mm ²)	Tensile strength	
	Based on JIS standard	SR235

8.3.2 Original design documents and determination of cross sections for structural analysis

As the design drawings used for the construction of the target sewer are available, details of the design cross section are determined based on both the results of investigation and data of the original design documents for obtaining the critical conditions. Table 8.31 compares the results of structural investigation and data obtained from the original drawings and shows the cross-sectional conditions used for structural analysis.

Table 8.31: Structural details of design cross section

		Classification		
Item		Structural investigation results	Standard drawing	Design cross section
Internal dimensions (mm)		$\phi 1,230$	$\phi 1,210$	$\phi 1,230$
Overburden thickness (m)		3.95–5.40		3.95–5.40
Compressive strength of concrete (N/mm ²)		21.2		21.2
Member thickness (mm)		86.0	103	86.0
Concrete cover (mm)	Inside	30.0	24.0	30.0
	Outside		24.0	24.0
Rebar diameter and spacing (mm)	Inside	$\phi 7.0@81$	Reinforcing bars of unknown diameter at 81 mm spacing	$\phi 7.0@81$
	Outside		Reinforcing bars of unknown diameter at 81 mm spacing	$\phi 7.0@81$
Rebar strength (N/mm ²)	Yield strength			235
	Tensile strength			380
	Based on JIS standard	Steel wire: SR235 or equivalent		SR235

8.3.3 General conditions for structural analysis

(1) Burial conditions, cross-sectional dimensions and rebar arrangements

Figure 8.38 shows the burial conditions of the existing sewer, its general structural dimensions, rebar arrangements and other structural details. The cross section of a sewer with standard renovation is also shown.

Figure 8.38: Cross section of sewer for structural analysis and renovation design: (a) general structural dimensions and burial conditions; (b) structural details of existing sewer; (c) cross section of sewer with standard renovation

(2) Support conditions

In view of the fact that typical drawings used for other projects around the time of completion (1929) specified 90-degree concrete foundations, the foundation was assumed to be a 90-degree fixed support structure; refer to Fig. 8.39.

Figure 8.39: Standard drawing (1929)

(3) Material properties

The material properties of the concrete, grouting materials, rebars and profiled steel sheets of the renovation layer are summarised in Table 8.32.

Table 8.32: Material properties

Material	Item	Specification	Unit	Remarks
Concrete members	Compressive strength	21.2	N/mm ²	Minimum test value
	Tensile strength	1.76	N/mm ²	JSCE (2013)
	Modulus of elasticity	23.6	kN/mm ²	"
	Poisson's ratio	0.2		"
	Fracture energy	80.9	N/m	"
Rebar	Yield strength	235	N/mm ²	Test
	Modulus of elasticity	200	kN/mm ²	JSCE (2013)
Grout (Mortar No. 2)	Compressive strength	21.0	N/mm ²	Design value
	Tensile strength	1.83	N/mm ²	"
	Modulus of elasticity	6.60	kN/mm ²	"
	Poisson's ratio	0.25		"
Grout (Mortar No. 3)	Fracture energy	17.6	N/m	"
	Compressive strength	35.0	N/mm ²	Design value
	Tensile strength	2.92	N/mm ²	"
	Modulus of elasticity	22.0	kN/mm ²	"
Profiled steel sheet #79SW	Poisson's ratio	0.22		"
	Fracture energy	70.8	N/m	"
	Yield strength	210	N/mm ²	Design value
	Modulus of elasticity	170	kN/mm ²	"
	Cross-sectional area	1571	mm ² /m	"

(5) Load conditions

Since the overburden thickness along this sewer line exceeds $2D_o$ (D_o : outside diameter of pipe) in some sections, it was judged that the most critical load conditions would occur when the earth pressure from the loosening zone is taken into consideration under the maximum overburden thickness (5.40 m). Live loads were taken into account in the perpendicular direction. Load conditions are calculated based on relevant codes (JRA, 2013a-b).

1) Static earth pressure (Fig. 8.40)

Static earth pressure (kN/m ²)		
Vertical load	Horizontal load	
P_{vd}	P_{hd1}	P_{hd2}
65.45	19.64	26.20

Figure 8.40: Static earth pressure

$$P_{vd} = \frac{B1 \cdot (\gamma - c / B1)}{K_0 \cdot \tan \phi} (1 - e^{-K_0 \cdot \tan \phi \cdot h / B1}) \quad (\text{kN/m}^2) \quad (8.8)$$

$$\text{where } B1 = R_0 \cdot \cot \left(\frac{45^\circ + \phi / 2}{2} \right);$$

P_{vd} : vertical earth pressure (loosening earth pressure); R_0 : excavation radius reflecting loosening width (= 1.482 m); γ : unit weight of soil (= 15.6 kN/m³; weighted average); c : cohesion of soil (= 2.7 kN/m²; weighted average); ϕ : angle of shear resistance of soil (= 7°; weighted average); K_0 : coefficient of static earth pressure (1.0 for calculation of loosening earth pressure); h : overburden thickness (5.4 m).

$$P_{hd1} = K_0 \cdot P_{vd} \text{ (kN/m}^2\text{)} \quad (8.9)$$

$$P_{hd2} = K_0 \cdot (P_{vd} + \gamma \cdot D_o) \text{ (kN/m}^2\text{)} \quad (8.10)$$

where P_{hd1} , P_{hd2} : horizontal earth pressure; K_0 : coefficient of static earth pressure (= 0.3); D_o : outside diameter of pipe (= 1.402 m).

2) Live loads (Fig. 8.41)

$$P_{vl} = \frac{2Pl \cdot (1+i) \cdot \beta}{C \cdot (a + 2h \cdot \tan \theta)} \text{ (kN/m}^2\text{)} \quad (8.11)$$

where P_{vl} : vertical live load; Pl : rear wheel load (= 100 kN); i : impact factor (= 0.110); β : reduction factor (= 0.9); C : overall vehicle width (= 2.75 m); a : ground contact width in the longitudinal direction (= 0.2 m); θ : load distribution angle (= 45°).

Figure 8.41: Live loads

(6) Analysis model

Figures 8.42 and 8.43 show FE models for structural analysis under normal load conditions and under seismic load conditions, respectively. In view of the symmetry, a half cross-sectional model is used for structural analysis under normal loads. In the seismic performance evaluation, the ground is modelled with finite elements having sufficient coverage for pipe–soil coupled analysis.

Figure 8.42: FE model for structural analysis under normal loads

Figure 8.43: FE model for seismic performance analysis

8.3.4 Numerical results under normal load conditions

(1) Existing cross section

Figures 8.44 and 8.45 show the cracking patterns, sectional forces and structural deformations based on the FE model of the existing cross section.

Figure 8.44: Cracking pattern and structural deformation (existing cross section)

Figure 8.45: Sectional forces (existing cross section)

(2) Standard renovation cross section with Mortar No. 2

Figures 8.46 and 8.47 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with Mortar No. 2.

Figure 8.46: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 2)

Figure 8.47: Sectional forces (standard renovation cross section, Mortar No. 2)

(3) Standard renovation cross section with Mortar No. 3

Figures 8.48 and 8.49 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with Mortar No. 3.

Figure 8.48: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 3)

Figure 8.49: Sectional forces (standard renovation cross section, Mortar No. 3)

8.3.5 Verification of safety under normal load conditions

The results of safety verification on the existing sewer and the other two renovation conditions are shown in Table 8.34. Based on these results, the following comments are made:

- In the serviceability limit state, the existing sewer will not meet the performance requirements because the load coefficient for cracking is less than 1.0. The standard renovation cross section with Mortar No. 2 or No. 3 will satisfy the performance requirements because the load coefficient for cracking is greater than 1.0.
- In the ultimate limit state, the existing sewer will not meet the performance requirements because its maximum load coefficient is less than 2.5. The standard renovation cross section with Mortar No. 2 or No. 3 will satisfy the performance requirements because the maximum load coefficient exceeds 2.5.

Table 8.34: Results of safety verification based on load coefficients

Renovation condition		Perpendicular live load		Judgement	Remarks
Cross section	Mortar	Cracking load coefficients	Maximum load coefficients		
Existing cross section		0.70	1.20	NG	
Standard renovation	No. 2	1.20	3.39	OK	
	No. 3	1.50	3.80	OK	
Required load coefficients		> 1.0	≥ 2.5		

8.3.6 Results of seismic performance analysis

(1) Existing cross section

1) Level 1 earthquake ground motion

Figure 8.50 shows the cracking and rebar yielding of the existing cross section under Level 1 earthquake ground motion.

2) Level 2 earthquake ground motion

Figure 8.51 shows the cracking and rebar yielding of the existing cross section under Level 2 earthquake ground motion. Table 8.35 shows the verification results under Level 2 ground motion.

Table 8.35: Verification results for existing cross section under Level 2 earthquake ground motion

Cross section		Existing cross section ($\phi 1,230$)							
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Ocean Type 2)			
Verification item		Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value
Maximum compressive strain		Less than 0.0031		OK	0.0031	Less than 0.0031		OK	0.0031
Shear forceTop at check point (kN)	1	30.41	0.96	OK	31.56	19.51	0.62	OK	31.56
	2	18.64	0.71	OK	26.30	18.16	0.58	OK	31.56
	3	14.84	0.56	OK	26.30	15.37	0.49	OK	31.56
	Side 4	41.39	1.31	NG	31.56	19.62	0.62	OK	31.56
	5	37.75	1.20	NG	31.56	14.00	0.44	OK	31.56
	6	12.92	0.49	OK	26.30	12.36	0.39	OK	31.56
	Bottom 7	13.88	0.53	OK	26.30	13.16	0.42	OK	31.56
	8	27.74	0.88	OK	31.56	10.17	0.32	OK	31.56
	9	27.76	0.88	OK	31.56	17.90	0.57	OK	31.56
	10	22.07	0.70	OK	31.56	21.39	0.68	OK	31.56
	11	16.26	0.62	OK	26.30	16.75	0.53	OK	31.56
	Side 12	19.39	0.61	OK	31.56	17.54	0.56	OK	31.56
	13	32.26	1.02	NG	31.56	23.73	0.75	OK	31.56
	14	34.49	1.09	NG	31.56	17.55	0.56	OK	31.56
	Top 15	9.52	0.36	OK	26.30	11.04	0.35	OK	31.56
	16	17.91	0.57	OK	31.56	13.19	0.42	OK	31.56
Final judgement		NG				OK			

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Figure 8.50: Cracking and rebar yielding in existing cross section (Level 1 earthquake ground motion)

Figure 8.51: Cracking and rebar yielding in existing cross section (Level 2 earthquake ground motion)

(2) Renovation with Mortar No. 2

Figure 8.52 shows the cracking and rebar yielding under Level 2 earthquake ground motion of a standard renovation cross section with Mortar No. 2. Table 8.36 shows the verification results.

Table 8.36: Verification results for standard renovation cross section with Mortar No. 2 under Level 2 earthquake ground motion

Cross section		Standard renovation cross section (φ1,130)								
Mortar		Mortar No. 2								
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Inland Type 2)				
Verification item		Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value	
Maximum compressive strain		Less than 0.0031		OK	0.0031	Less than 0.0031		OK	0.0031	
Shear force at check point (kN)	Top	1	59.40	0.25	OK	241.98	45.73	0.19	OK	241.98
		2	46.30	0.24	OK	193.43	32.74	0.14	OK	232.11
		3	23.97	0.11	OK	220.72	24.57	0.11	OK	220.72
	Side	4	50.67	0.27	OK	187.00	41.43	0.22	OK	187.00
		5	51.46	0.31	OK	167.46	36.12	0.22	OK	167.46
		6	23.38	0.22	OK	107.22	23.25	0.18	OK	128.67
	Bottom	7	16.11	0.31	OK	51.82	18.98	0.31	OK	62.19
		8	36.85	0.68	OK	54.29	25.48	0.47	OK	54.29
		9	35.16	0.66	OK	53.32	30.64	0.57	OK	53.32
		10	29.81	0.55	OK	54.29	35.00	0.64	OK	54.29
		11	25.51	0.41	OK	62.19	22.68	0.36	OK	62.19
		12	35.14	0.27	OK	128.67	30.53	0.24	OK	128.67
	Side	13	71.56	0.43	OK	167.46	36.56	0.22	OK	167.46
		14	51.16	0.33	OK	155.83	32.46	0.17	OK	187.00
	Top	15	18.43	0.10	OK	183.93	19.47	0.11	OK	183.93
		16	32.04	0.14	OK	232.11	31.24	0.13	OK	232.11
Final judgement		OK				OK				

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Figure 8.52: Cracking and rebar yielding in standard renovation cross section with Mortar No. 2 (Level 2 earthquake ground motion)

(3) Renovation with Mortar No. 3

Figure 8.53 shows the cracking and rebar yielding under Level 2 earthquake ground motion of a standard renovation cross section with Mortar No. 3. Table 8.37 shows the verification results.

Table 8.37: Verification results for standard renovation cross section with Mortar No. 3 under Level 2 earthquake ground motion

Cross section		Standard renovation cross section (φ1,130)								
Mortar		Mortar No. 3								
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Inland Type 2)				
Verification item		Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value	
Maximum compressive strain		0.0005		OK	0.0031	Less than 0.0031		OK	0.0031	
Shear force at check point (kN)	Top	1	63.02	0.23	OK	278.21	56.96	0.20	OK	278.21
		2	37.31	0.17	OK	222.21	40.90	0.15	OK	266.65
		3	26.35	0.12	OK	211.08	26.74	0.11	OK	253.29
	Side	4	53.37	0.25	OK	213.76	47.83	0.22	OK	213.76
		5	53.28	0.28	OK	190.86	40.98	0.21	OK	190.86
		6	26.13	0.22	OK	121.16	29.06	0.20	OK	145.39
	Bottom	7	18.25	0.17	OK	105.54	19.34	0.15	OK	126.65
		8	39.62	0.39	OK	102.14	29.12	0.29	OK	102.14
		9	37.63	0.38	OK	99.12	36.99	0.37	OK	99.12
	Side	10	32.11	0.33	OK	85.12	40.47	0.40	OK	102.14
		11	23.19	0.22	OK	105.54	25.83	0.20	OK	126.65
		12	38.81	0.27	OK	145.39	35.51	0.24	OK	145.39
	Top	13	74.40	0.39	OK	190.86	43.35	0.23	OK	190.86
		14	51.20	0.29	OK	178.13	43.82	0.20	OK	213.76
		15	20.56	0.10	OK	211.08	22.62	0.09	OK	253.29
		16	39.41	0.18	OK	222.21	37.03	0.14	OK	266.65
Final judgement		OK				OK				

■ Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

Ground motion	Cracking	Rebar yielding
Inland Type 1	<p>Red line: cracking</p>	<p>Red line: rebar yielding</p>
Inland Type 2	<p>Red line: cracking</p>	<p>No rebar yielding</p>

Figure 8.53: Cracking and rebar yielding in standard renovation cross section with Mortar No. 3 (Level 2 earthquake ground motion)

8.3.7 Verification of safety under earthquake loading

The results of seismic safety verification on the existing sewer and the other two types of renovation conditions are shown in Table 8.38. Based on these results, the following comments are made:

- The verification results indicate that under Level 1 earthquake ground motion, the existing sewer meets the earthquake resistance requirements.
- The verification results indicate that under Level 2 earthquake ground motion, the existing sewer does not meet the earthquake resistance requirements, but the standard renovation cross section with Mortar No. 2 or Mortar No. 3 satisfies the earthquake resistance requirements.

Table 8.38: Results of safety verification under earthquake loading

Renovation condition		Level 1 earthquake ground motion	Level 2 earthquake ground motion			Remarks
Cross section	Mortar		Ultimate displacement	Shear force	Judgement	
Existing cross section		OK	OK	NG	NG	
Standard renovation cross section	No. 2		OK	OK	OK	
	No. 3		OK	OK	OK	

Note: Ultimate displacement under Level 2 earthquake ground motion is verified by checking the maximum compressive strain.

8.3.8 Safety verification of local buckling at the bottom of the pipe

Safety verification on the local buckling of the renovation layer at the bottom of the pipe is deemed unnecessary; refer to Section 5.4 for an explanation.

8.3.9 Determination of renovation methods

(1) Structural strength

Though the existing sewer can withstand Level 1 earthquake force, it is not strong enough to sustain Level 2 earthquake ground motion, and it fails to meet the performance requirements under normal load conditions. Therefore, structural renovation has to be performed on this sewer line. The required structural strength can be achieved by employing the standard renovation cross section with Mortar No. 2 or Mortar No. 3.

(2) Achieving the required discharge capacity

The discharge capacity at each section of the renovated sewer is calculated and shown in Table 8.39. For details of flow ratio computation, refer to Example I.

(3) Conclusion

Based on the various analysis results discussed above, sewer renovation will be carried out for this sewer line to strengthen its earthquake resistance, and to mitigate flooding damage by keeping its discharge capacity adequate. The renovation method adopted for this sewer line is to use the standard renovation cross section with Mortar No. 2, so as to achieve the required structural strength against Level 2 earthquake ground motion economically. The renovation plan for each section of this sewer line is listed in Table 8.39.

Table 8.39: List of renovation plans (Example III)

Section No.		4	5	6	7	8	9	10
Sewer length (m)		10.39	7.39	24.21	60.63	80.36	37.36	11.30
Dimensions	Existing sewer	φ1,210	φ1,210	φ1,210	φ1,210	φ1,210	φ1,210	φ1,210
	After renovation	φ1,110	φ1,110	φ1,110	φ1,110	φ1,110	φ1,110	φ1,110
Slope (‰)	Existing sewer	0.55	0.55	0.55	0.55	0.55	0.91	0.91
	After renovation	0.55	0.55	0.55	0.55	0.55	0.91	0.91
Flow ratio	Existing sewer	1.73	1.73	1.73	1.11	0.99	1.65	0.92
	After renovation	1.79	1.79	1.79	1.15	1.03	1.70	0.95

8.4 Example IV: Circular Sewer (Sand-filled Foundation)

8.4.1 Internal investigation of sewer

(1) Investigation of internal cross section and damage condition

The sewer line investigated here is a circular pipe, and its internal diameter and damage condition at each section are shown in Table 8.40. Based on preliminary inspections, it was decided to conduct a structural investigation on Section No. 1, where the structural deterioration was found to be most severe.

Table 8.40: Structural conditions of inspected sewer line (Example IV)

Section No.	Results of inspection (measurements)		Sewer conditions
	Diameter (mm)	Length (m)	Observed damage and judgement
1	φ1,500	76.60	Longitudinal cracking, rebar exposure
2	φ1,500	67.65	Rebar exposure
3	φ1,500	30.85	Rebar exposure
4	φ1,500	21.20	No damage
5	φ1,500	88.15	No damage
6	φ1,500	62.55	Rebar exposure
7	φ1,500	64.50	Rebar exposure
8	φ1,500	27.00	No damage
9	φ1,500	41.30	No damage
10	φ1,500	32.35	No damage
11	φ1,500	34.95	No damage
12	φ1,500	14.50	No damage

(2) Investigation items and results

The items and results of sewer investigation are shown in Table 8.41.

Table 8.41: Investigation items and results

		Results
Item		Investigation results
Cross-sectional shape		Circular
Internal dimensions (mm)	Diameter	$\phi 1,500$
Overburden thickness (m)		0.93–2.35
Compressive strength of concrete (N/mm ²)		46.1–65.2
Member thickness (mm)		95.0
Concrete cover (mm)		31.0
Rebar diameter and spacing (mm)		$\phi 5.0@73$
Rebar strength (N/mm ²)	Yield strength	
	Tensile strength	
	Based on JIS standard	SR235

8.4.2 Original design documents and determination of cross sections for structural analysis

As the design drawings used for the construction of the target sewer are available, details of the design cross section are determined based on both the results of investigation and data of the original design documents for obtaining the critical conditions. Table 8.42 compares the results of structural investigation and data obtained from the original drawings and shows the cross-sectional conditions used for structural analysis.

Table 8.42: Structural details of design cross section

		Classification		
Item		Structural investigation results	Standard drawing	Design cross section
Internal dimensions (mm)		$\phi 1,500$	$\phi 1,500$	$\phi 1,500$
Overburden thickness (m)		0.93–2.35		0.93–2.35
Compressive strength of concrete (N/mm ²)		46.1		46.1
Member thickness (mm)		95.0	112.0	95.0
Concrete cover (mm)	Inside	31.0		31.0
	Outside			31.0
Rebar diameter and spacing (mm)	Inside	$\phi 5.0@73$		$\phi 5.0@73$
	Outside			$\phi 5.0@73$
Rebar strength (N/mm ²)	Yield strength			235
	Tensile strength			380
	Based on JIS standard	SR235		SR235

8.4.3 General conditions for structural analysis

(1) Burial conditions, cross-sectional dimensions and rebar arrangements

Figure 8.54 shows the burial conditions of the existing sewer, its general structural dimensions, rebar arrangements and other structural details. The cross section of a sewer with standard renovation is also shown.

Figure 8.54: Cross section of sewer for structural analysis and renovation design: (a) general structural dimensions and burial conditions; (b) structural details of existing sewer; (c) cross section of sewer with standard renovation

(2) Support conditions

As shown in Fig. 8.55, the as-built drawing shows a sand-filled foundation and specifies the compacted thickness as being up to the level of the top of the sewer. Therefore, the foundation structure is assumed to have a 120-degree range of support area for reaction.

Figure 8.55: As-built drawing (1970)

(3) Material properties

The material properties of the concrete, grouting materials, rebars and profiled steel sheets of the renovation layer are summarised in Table 8.43.

Table 8.43: Material properties

Material	Item	Specification	Unit	Remarks
Concrete members	Compressive strength	46.1	N/mm ²	Minimum test value
	Tensile strength	2.96	N/mm ²	JSCE (2013)
	Modulus of elasticity	32.2	kN/mm ²	"
	Poisson's ratio	0.2		"
	Fracture energy	104.8	N/m	"
Rebar	Yield strength	235	N/mm ²	Test
	Modulus of elasticity	200	kN/mm ²	JSCE (2013)
Grout (Mortar No. 2)	Compressive strength	21.0	N/mm ²	Design value
	Tensile strength	1.83	N/mm ²	"
	Modulus of elasticity	6.60	kN/mm ²	"
	Poisson's ratio	0.25		"
	Fracture energy	17.6	N/m	"
Grout (Mortar No. 3)	Compressive strength	35.0	N/mm ²	Design value
	Tensile strength	2.92	N/mm ²	"
	Modulus of elasticity	22.0	kN/mm ²	"
	Poisson's ratio	0.22		"
	Fracture energy	70.8	N/m	"
Profiled steel sheet #79SW	Yield point	210	N/mm ²	Design value
	Modulus of elasticity	170	kN/mm ²	"
	Cross-sectional area	1571	mm ² /m	"

(4) Soil conditions

In view of the boring data obtained from a nearby location, soil conditions are assumed as shown in Table 8.44.

Table 8.44: Soil conditions

Boring data	Soil No.	Soil type	Depth (m)	Thickness, H_i (m)	Average N-value	Average shear wave velocity, V_{si} (m/s)	H_i/V_{si} (s)
6	1	1.50	1.50	6	168.60	0.009
	4						
	4	2	4.90	3.40	4	157.97	0.022
	45						
	50	3	7.80	2.90	48	376.42	0.008
	50						
	31						
	50	4	9.70	1.90	31	325.19	0.006
	50						
	50						
	50						
	50						
	50						
		Basement layer					
		Hard pan			> 50	400.00	

Evaluation of ground property: $T_g = 4 \sum_{i=1}^n \frac{H_i}{V_{si}} = 0.176$ (s), Class I

Classification of ground: $T_g < 0.2$, Class I; $0.2 \leq T_g < 0.6$, Class II; $0.6 \leq T_g$, Class III

(5) Load conditions

Since the overburden thickness along this sewer line is smaller than $2D_o$ (D_o : outside diameter of pipe), it was judged that the most critical load conditions would occur when normal earth pressure is taken into consideration under the minimum overburden thickness (0.93 m). Live loads were taken into account in the perpendicular direction. Load conditions are calculated based on relevant codes (JRA, 2013a-b).

1) Static earth pressure (Fig. 8.56)

Applied static earth pressures are shown in Fig. 8.56. The reaction due to the vertical earth pressure is obtained as

$$P_{rd} = \frac{P_{vd}}{\sin(120^\circ/2)} \quad (\text{kN/m}^2) \quad (8.12)$$

where P_{vd} : vertical earth pressure; P_{rd} : reaction due to vertical earth pressure. For details of earth pressure computation, refer to Example I. Note that the coefficient of horizontal earth pressure, K_o , is 0.3 for the present case.

Figure 8.56: Static earth pressure

2) Live loads (Fig. 8.57)

Figure 8.57: Live loads

Applied live loads are shown in Fig. 8.57. The reaction due to the vertical live load is obtained as

$$P_{rl} = \frac{P_{vl}}{\sin(120^\circ/2)} \quad (\text{kN/m}^2) \quad (8.13)$$

where P_{vl} : vertical live load; P_{rl} : reaction due to vertical live load. For details of live load computation, refer to Example III. Note that the impact factor, i , is 0.5 for the present case.

(6) Analysis model

Figures 8.58 and 8.59 show FE models for structural analysis under normal load conditions and under seismic load conditions, respectively. In view of the symmetry, a half cross-sectional model is used for structural analysis under normal loads. In the seismic performance evaluation, the ground is modelled with finite elements having sufficient coverage for pipe-soil coupled analysis. Regions where longitudinal cracking has occurred are modelled assuming full-depth cracking.

Figure 8.58: FE model for structural analysis under normal loads

Figure 8.59: FE model for seismic performance analysis

8.4.4 Numerical results under normal load conditions

(1) Existing cross section

Figures 8.60 and 8.61 show the cracking patterns, sectional forces and structural deformations based on the FE model of the existing cross section.

Figure 8.60: Cracking pattern and structural deformation (existing cross section)

Figure 8.61: Sectional forces (existing cross section)

(2) Standard renovation cross section with Mortar No. 2

Figures 8.62 and 8.63 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with Mortar No. 2.

Figure 8.62: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 2)

(3) Standard renovation cross section with Mortar No. 3

Figures 8.64 and 8.65 show the cracking patterns, sectional forces and structural deformations based on the FE model of the standard renovation cross section with Mortar No. 3.

Figure 8.63: Sectional forces (standard renovation cross section, Mortar No. 2)

Figure 8.64: Cracking pattern and structural deformation (standard renovation cross section, Mortar No. 3)

Figure 8.65: Sectional forces (standard renovation cross section, Mortar No. 3)

8.4.5 Verification of safety under normal load conditions

The results of safety verification on the existing sewer and the other two renovation conditions are shown in Table 8.45. Based on these results, the following comments are made:

- In the serviceability limit state, the existing sewer will not meet the performance requirements because it has already sustained severe cracking. The standard renovation cross section with Mortar No. 2 or No. 3 will satisfy the performance requirements because the load coefficient for cracking is greater than 1.0.
- In the ultimate limit state, the existing sewer will not meet the performance requirements because its maximum load coefficient is less than 2.5. The standard renovation cross section with Mortar No. 2 or No. 3 will satisfy the performance requirements because the maximum load coefficient exceeds 2.5.

Table 8.45: Results of safety verification based on load coefficients

Renovation condition		Perpendicular live load		Judgement Remarks
Cross section	Mortar	Cracking load coefficients	Maximum load coefficients	
Existing cross section			1.16	NG
Standard renovation	No. 2	1.45	3.27	OK
	No. 3	1.80	3.75	OK
Required load coefficients		> 1.0	≥ 2.5	

8.4.6 Results of seismic performance analysis

(1) Existing cross section

1) Level 1 earthquake ground motion

Figure 8.66 shows the cracking and rebar yielding of the existing cross section under Level 1 earthquake ground motion.

Figure 8.66: Cracking and rebar yielding in existing cross section (Level 1 earthquake ground motion)

2) Level 2 earthquake ground motion

Figure 8.67 shows the cracking and rebar yielding of the existing cross section under Level 2 earthquake ground motion. Table 8.46 shows the verification results under Level 2 ground motion.

Table 8.46: Verification results for existing cross section under Level 2 earthquake ground motion

Cross section		Existing cross section (φ1,500)								
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Ocean Type 2)				
Verification item		Response value		Response value/limit value	Judge-ment	Limit value	Response value/limit value		Judge-ment	Limit value
Maximum compressive strain		0.000312			OK	0.0031	Less than 0.0031		OK	0.0031
Shear force at check point (kN)	Top	1	19.86		NG	0.00	11.49		NG	0.00
		2	18.82	0.62	OK	30.51	14.83	0.41	OK	36.61
		3	8.27	0.27	OK	30.51	6.86	0.19	OK	36.61
		4	19.59	0.64	OK	30.51	13.18	0.36	OK	36.61
	Side	5	30.88	0.84	OK	36.61	15.91	0.43	OK	36.61
		6	19.97	0.65	OK	30.51	14.61	0.40	OK	36.61
		7	8.86	0.29	OK	30.51	6.53	0.18	OK	36.61
		8	21.46	0.70	OK	30.51	13.64	0.37	OK	36.61
	Bottom	9	26.57	0.73	OK	36.61	19.99	0.55	OK	36.61
		10	20.87	0.68	OK	30.51	17.85	0.49	OK	36.61
		11	10.07	0.33	OK	30.51	9.3	0.25	OK	36.61
		12	24.52	0.80	OK	30.51	16.36	0.45	OK	36.61
	Side	13	28.31	0.77	OK	36.61	15.57	0.43	OK	36.61
		14	14.09	0.46	OK	30.51	11.21	0.31	OK	36.61
	Top	15	5.72	0.19	OK	30.51	5.03	0.14	OK	36.61
		16	19.93	0.54	OK	36.61	9.98	0.27	OK	36.61
Final judgement		NG				NG				

Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

The shear strength of existing members is assumed to be zero because of longitudinal cracking.

Figure 8.67: Cracking and rebar yielding in existing cross section (Level 2 earthquake ground motion)

(2) Renovation with Mortar No. 2

Figure 8.68 shows the cracking and rebar yielding under Level 2 earthquake ground motion of a standard renovation cross section with Mortar No. 2. Table 8.47 shows the verification results.

Figure 8.68: Cracking and rebar yielding in standard renovation cross section with Mortar No. 2 (Level 2 earthquake ground motion)

Table 8.47: Verification results for standard renovation cross section with Mortar No. 2 under Level 2 earthquake ground motion

Cross section		Standard renovation cross section (φ1,360)								
Mortar		Mortar No. 2								
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Inland Type 2)				
Verification item		Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value	
Maximum compressive strain		0.0016		OK	0.0031	Smaller than 0.0031		OK	0.0031	
Shear force at check point (kN)	Top	1	53.93	0.17	OK	317.64	50.00	0.16	OK	317.64
		2	35.78	0.10	OK	344.92	34.57	0.10	OK	344.92
		3	23.59	0.09	OK	265.22	12.96	0.04	OK	318.26
	Side	4	32.54	0.12	OK	277.57	27.64	0.10	OK	277.57
		5	44.19	0.19	OK	228.80	38.07	0.17	OK	228.80
		6	30.31	0.17	OK	178.17	33.25	0.19	OK	178.17
	Bottom	7	18.64	0.30	OK	61.27	11.88	0.16	OK	73.53
		8	25.10	0.48	OK	51.93	22.05	0.35	OK	62.32
		9	36.16	0.62	OK	58.36	37.86	0.65	OK	58.36
		10	23.32	0.45	OK	51.93	22.41	0.36	OK	62.32
		11	14.91	0.20	OK	73.53	14.10	0.19	OK	73.53
		12	51.65	0.29	OK	178.17	35.26	0.20	OK	178.17
	Side	13	56.45	0.30	OK	190.67	37.02	0.16	OK	228.80
		14	28.70	0.12	OK	231.31	24.51	0.09	OK	277.57
	Top	15	11.08	0.04	OK	265.22	11.74	0.04	OK	318.26
		16	36.10	0.10	OK	344.92	33.00	0.10	OK	344.92
Final judgement		OK				OK				

Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

The shear strength of existing members is assumed to be zero because of longitudinal cracking.

(3) Renovation with Mortar No. 3

Figure 8.69 shows the cracking and rebar yielding under Level 2 earthquake ground motion of a standard renovation cross section with Mortar No. 3. Table 8.48 shows the verification results.

Table 8.48: Verification results for standard renovation cross section with Mortar No. 3 under Level 2 earthquake ground motion

Cross section		Standard renovation cross section (φ1,360)								
Mortar		Mortar No. 3								
Input ground motion		Level 2 earthquake ground motion (Inland Type 1)				Level 2 earthquake ground motion (Inland Type 2)				
Verification item		Response value	Response value/limit value	Judge-ment	Limit value	Response value	Response value/limit value	Judge-ment	Limit value	
Maximum compressive strain		0.0003		OK	0.0031	Less than 0.0031		OK	0.0031	
Shear force at check point (kN)	Top	1	66.77	0.18	OK	372.33	52.68	0.14	OK	372.33
		2	49.80	0.13	OK	398.00	35.99	0.09	OK	398.00
		3	14.36	0.04	OK	366.76	14.39	0.04	OK	366.76
	Side	4	44.23	0.14	OK	319.06	28.81	0.09	OK	319.06
		5	53.60	0.20	OK	261.89	39.05	0.15	OK	261.89
		6	34.36	0.17	OK	202.54	35.17	0.17	OK	202.54
	Bottom	7	13.17	0.20	OK	64.73	13.09	0.17	OK	77.67
		8	22.17	0.41	OK	54.34	22.16	0.34	OK	65.20
		9	42.07	0.69	OK	60.81	38.89	0.64	OK	60.81
		10	24.33	0.45	OK	54.34	22.55	0.35	OK	65.20
		11	17.50	0.27	OK	64.73	15.78	0.20	OK	77.67
		12	56.94	0.28	OK	202.54	37.18	0.18	OK	202.54
	Side	13	36.10	0.14	OK	261.89	38.98	0.15	OK	261.89
		14	23.79	0.07	OK	319.06	25.57	0.08	OK	319.06
	Top	15	14.96	0.04	OK	366.76	13.04	0.04	OK	366.76
		16	46.43	0.12	OK	398.00	34.48	0.09	OK	398.00
Final judgement		OK				OK				

Member with rebar yielding (structural member coefficient $\gamma_b = 1.56$)

■ The shear strength of existing members is assumed to be zero because of longitudinal cracking.

Figure 8.69: Cracking and rebar yielding in standard renovation cross section with Mortar No. 3 (Level 2 earthquake ground motion)

8.4.7 Verification of safety under earthquake loading

The results of seismic safety verification on the existing sewer and the other two types of renovation conditions are shown in Table 8.49. Based on these results, the following comments are made:

- The verification results indicate that under Level 1 earthquake ground motion, the existing sewer meets the earthquake resistance requirements.
- The verification results indicate that under Level 2 earthquake ground motion, the existing sewer does not meet the earthquake resistance requirements, but the standard renovation cross section with Mortar No. 2 or Mortar No. 3 satisfies the earthquake resistance requirements.

Table 8.49: Results of safety verification under earthquake loading

Renovation condition		Level 1 earthquake ground motion	Level 2 earthquake ground motion		Remarks
Cross section	Mortar		Ultimate displace- ment	Shear force Judge-ment	
Existing cross section		OK	OK	NG	NG
Standard renovation cross section	No. 2		OK	OK	OK
	No. 3		OK	OK	OK

Note: Ultimate displacement under Level 2 earthquake ground motion is verified by checking the maximum compressive strain.

8.4.8 Safety verification of local buckling at the bottom of the pipe

Safety verification on the local buckling of the renovation layer at the bottom of the pipe is deemed unnecessary; refer to Section 5.4 for an explanation.

8.4.9 Determination of renovation methods

(1) Structural strength

Though the existing sewer can withstand Level 1 earthquake force, it is not strong enough to sustain Level 2 earthquake ground motion, and it fails to meet the performance requirements under normal load conditions. Therefore, structural renovation has to be performed on this sewer line. The required structural strength can be achieved by employing the standard renovation cross section with Mortar No. 2 or Mortar No. 3.

(2) Achieving the required discharge capacity

The discharge capacity at each section of the renovated sewer is calculated and shown in Table 8.50. For details of flow ratio computation, refer to Example I.

(3) Conclusion

Based on the various analysis results discussed above, sewer renovation will be carried out for this sewer line to strengthen its earthquake resistance, and to mitigate flooding damage by keeping its discharge capacity adequate. The renovation method adopted for this sewer line is to use the standard renovation cross section with Mortar No. 2, so as to achieve the required structural strength against Level 2 earthquake ground motion economically. The renovation plan for each section of this sewer line is listed in Table 8.50.

Table 8.50: List of renovation plans (Example IV)

Section No.		1	2	3	4	5	6	7
Sewer length (m)		76.60	67.65	30.85	21.20	88.15	62.55	64.50
Dimensions	Existing sewer	φ1,500	φ1,500	φ1,500	φ1,500	φ1,500	φ1,500	φ1,500
	After renovation	φ1,360	φ1,360	φ1,360	φ1,360	φ1,360	φ1,360	φ1,360
Slope (‰)	Existing sewer	0.4	1.3	1.0	1.2	1.3	1.2	1.7
	After renovation	0.4	1.3	1.0	1.2	1.3	1.2	1.7
Flow ratio	Existing sewer	25.47	19.75	14.83	7.82	11.76	6.73	6.48
	After renovation	25.50	19.77	14.85	7.83	11.77	6.73	6.49

Section No.		8	9	10	11	12
Sewer length (m)		27.00	41.30	32.35	34.95	14.5
Dimensions	Existing sewer	φ1,500	φ1,500	φ1,500	φ1,500	φ1,500
	After renovation	φ1,360	φ1,360	φ1,360	φ1,360	φ1,360
Slope (‰)	Existing sewer	0.8	2.0	1.1	0.7	-13.6
	After renovation	0.8	2.0	1.1	0.7	3.4
Flow ratio	Existing sewer	3.09	3.25	15.07	9.76	
	After renovation	3.09	3.25	15.09	9.77	2.01

References

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