〈ノート〉

Hydraulic Model Experiments on Akabane-West Trunk Sewer Basin

── Research for Issues and Countermeasures Concerning Complex Hydraulic Phenomena in Long Inverted Siphon ──

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Abstract

In a long and deep inverted siphon at large difference of ground level, it is anticipated that complex and non-steady hydraulic phenomena, which cause overflow from manholes and blow manhole covers away, take place. This study examined storm water flow and air supply and exhaust in a long inverted siphon using hydraulic model experiments. This study also examined that a long inverted siphon and countermeasure structure against large drop affected hydraulic level. Finally, this study examined countermeasures that have minimum structural improvement to sewer system.

Keyword : long inverted siphon, large drop, complex hydraulic phenomena, hydraulic model experiment

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1. Introduction

In Akabane-West trunk sewer basin located mainly in Kita Word, Tokyo, most of storm water flows down in Akabane-West trunk sewer to Shingashi River. Due to lack of flow capacity of the trunk sewer, flooding has frequently occurred. Four branch sewers including the Akabane-West major branch sewer were planned to construct as relief sewers to prevent flooding.

These relief sewers must be installed in very deep underground due to various existing underground objects. Thus, deep inlet manhole should be constructed. Also, the relief sewers must be long inverted siphon. From these conditions, it was anticipated that the relief sewers would have unsteady and complex hydraulic phenomena from inlet manholes to outlet into the river. These hydraulic phenomena may cause overflow from manholes or may lead to accident that manhole covers may be blown away at large difference of ground level.

This research was carried out to verify that the relief sewers would have enough capacity to inflow storm water in the basin, and to verify the relief sewers have sufficient ability to remove excess air in the storm water flow, using hydraulic model experiments. The hydraulic model experiments were carried out to propose efficient and effective strategic plans to safely realize storm water drainage system.

2. Research target facilities

The research targets were the four relief sewers which consisted of four branch sewers including the Akabane-West major branch sewer. The relief sewers had 4 km of total length, 1.2 km of long inverted siphon and deep inlets as shown in **Fig. 1**. Relief sewer A had 2,400 mm of diameter and 1.3 km of length. Relief sewer B had 2,800 mm of diameter and 0.6 km of

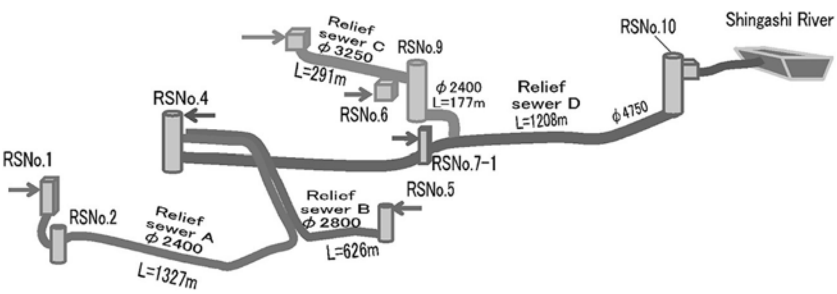

Fig. 1 Diagram of the research target facilities (four relief sewers)

length. Relief sewer C had 2,400 mm to 3,250 mm of diameter and 0.5 km of length. Relief sewer D had 4,750 mm of diameter and 1.2 km of length. The majority of the sewers were inverted siphon.

3. Hydraulic model experiments

Large-scale complex sewer system like this system tends to have following phenomena :

・Occurrence of wave and excess exhaust air

In inverted siphon, when the flow reaches a downstream manhole, the flow is temporarily stagnated and flows upstream as wave. Air trapped in the flow goes upstream and blows out from an upstream manhole

・Gushing residual air

When the flow is pressurized inside the sewer and trapped air remains in the flow, pressurized residual air gushes out through a manhole. Factors to trap air in the flow are 1) that air above the water surface in sewer is trapped trapping air after wave goes passed upstream and sewer is full, and 2) that during inflow falls down from inlet high above the sewer, air is trapped to inflow and goes to the sewer.

・Increase of hydraulic level

The following conditions may result in an unacceptable head loss, which increases hydraulic level to the ground level, such as sewer becomes full, inflow comes from multiple directions, interior structure of manhole has multiple stages and sewer has a succession of bending.

These phenomena may cause substantial overflow through manholes or accidents resulting from splashing manhole covers. The occurrence of these phenomena depends on structure of the facilities and flow conditions. Therefore, hydraulic model experiments should be conducted in advance[1].

4. Research process and the range of reproduction of hydraulic models

In this research, hydraulic model experiments were conducted using the following process ; 1) compile hydraulic problems on the initially designed facilities, 2) examine sewer system to ensure enough flow capacity and 3) verify the effect of countermeasures and decide the optimal facility design as shown in **Fig. 2**.

The range of reproduction of hydraulic model included relief sewers, inflow manholes that connected to the relief sewers and inflow sewers to the manholes. The reproduced length of inflow sewers was ten times of their diameter. **Fig. 3** shows photographs, model

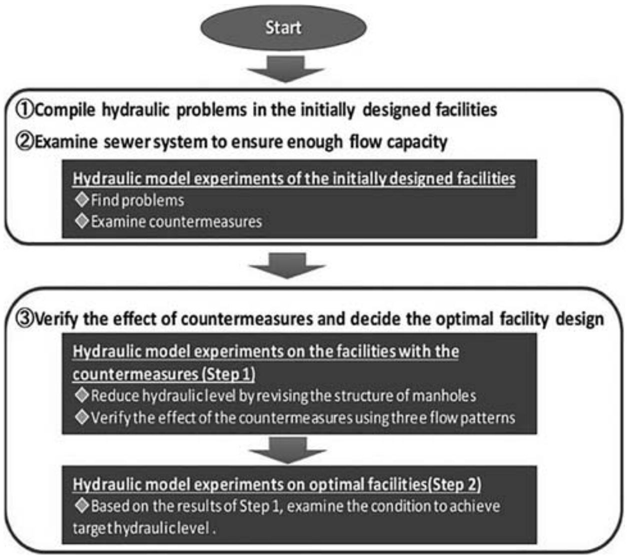

Fig. 2　Research process

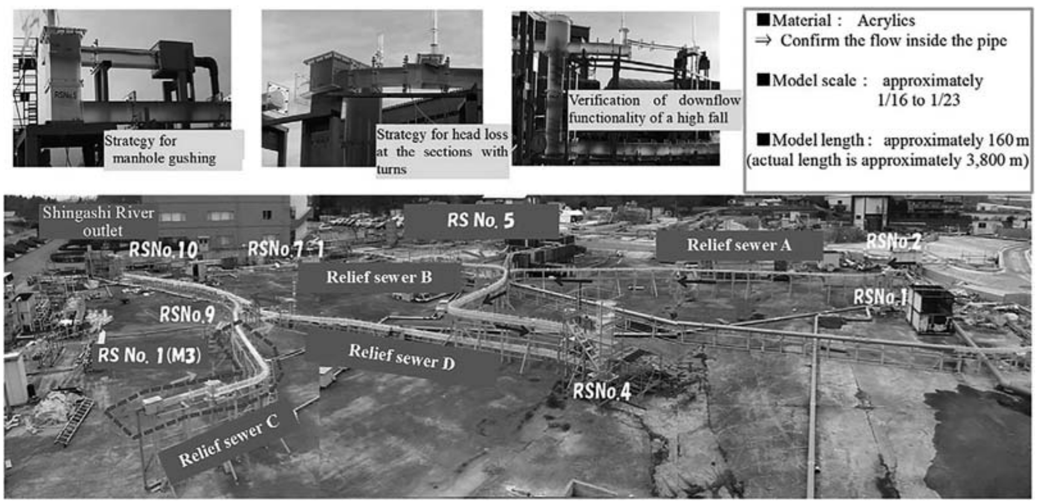

Fig. 3　Hydraulic model experiment facilities

scale of the hydraulic model experiment facility. Size of model experiment facility was set based on Fluid similarity rule.

5. Compilation of hydraulic problems on the initially designed facilities

5. 1 Flow conditions on hydraulic model experiments

Flow conditions on hydraulic model experiments for original design facilities are shown in **Table 1**.

Peak value of 50 mm/h precipitation was the same as planned flow.

Because flow capacity could not meet planned flow rate when discharge rate regulation existed, Case 3 in which flow rate was reduced was set. Reduced flow rate was that marginal flow capacity of existing facilities was sutracted from planned flow rate.

Table 1 Flow conditions

Case Name	Flow Amount Condition
Case 1 : 50 mm/h precipitation concentrated in the middle of the rainfall event	Typical rainfall condition in Tokyo. Rainfall intensity is 50 mm/hr and precipitation was concentrated in the middle of the rainfall event. Flow rate changed due to the rainfall pattern.
Case 2 : 50 mm/h constant peak	This condition ensured safety when the situation is worse than case 1. The same amount of rainfall as the peak flow in case 1 continuously flowed into inflow sewers.
Case 3 : 50 mm/h reduced flow	This condition was a reduced flow rate from case 2. ※ Reduced flow rate was set in original design. By implementing flow reduction measures before storm water flows into inflow sewers flow rate was reduced. This was the condition for the final goal (step 2) in the hydraulic model experiments.

5. 2 Dynamic water level for flow amount conditions

The hydraulic model experiments of the initially designed facilities were conducted based on the flow conditions as shown in **Table 1**. **Table 2** shows the difference between hydraulic level and ground level as the results of the experiments.

The hydraulic problems on the initially designed facilities were summarized below.

In the initially designed facilities, the hydraulic level went upward due to the complex structure and impact of pressure pipe conditions. As a result, flooding was observed at some measurement points (manhole locations).

Assuming that the target hydraulic level was lower than −1.0 m from the ground level, the following results were obtained :

- In case 1, the target hydraulic level was not achieved at two manholes (RS No. 5 and RS No. 10).
- In case 2, the target hydraulic level was not achieved at most of the measurement points (manholes). Also, the level lower than GL was not achieved.
- Even after implementing the flow rate reduction measures in case 3, RS No. 1, RS No. 5, RS No. 9, and RS No. 10 did not achieve the target hydraulic level.
- The ground level of RS No. 10 was low because it was located near the river. Therefore, achieving the target hydraulic level was quite difficult at this location.
- Since initially designed facilities already implemented countermeasures for air flow into sewers based on previous knowledge[2], countermeasures contributed to reduce gushing residual air.

Table 2 Difference between hydraulic level and ground level (m) (Initially designed facilities)

Pipeline	Measurement Point	Ground Level (m)	Planned Flow Rate (m^3/s)	Reduced Flow Rate (m^3/s)	Case1 (m)	Case2 (m)	Case3 (m)
Akabane-Nishi major branch sewer 【A】	RS No. 1	10.520	7.059	7.059	−4.094	4.214	0.886
	RS No. 2	17.000	—	—	−11.919	−3.452	−6.117
Akabane-Nishi major branch sewer 【B】	RS No. 5	6.050	4.902	1.698	0.596	3.009	−0.066
Akabanedai-San major branch sewer 【C】	RS No. 1 (M3)	8.390	5.887	5.231	−3.402	1.517	−1.824
	RS No. 6	8.140	0.925	0.088	−4.415	1.853	−1.369
	RS No. 9	6.430	—	—	−1.746	3.248	0.304
Akabanedai-Ichi/Iwabuchi-Machi major branch sewer 【D】	RS No. 4	20.800	3.718	3.751	−16.330	−12.073	−14.787
	RS No. 7-1	8.550	1.742	0.122	−4.029	0.353	−2.845
	RS No. 10	4.680	—	—	−0.204	3.288	0.886

□ : Lower than GL-1.0 m □ : Between GL-1.0 and GL ■ : Higher than GL

6. Examination to ensure enough flow capacity

Considering the hydraulic phenomena observed in the experiments of initially designed facilities, countermeasures for three facilities where hydraulic level exceeded the ground level in case 3, were devised based on the place where dynamic water level rose and value of dynamic water level from following points of view.

【Points of view for countermeasures】

(1) Manhole RS No. 1 was highly influenced by the increased hydraulic level at RS No. 2.

(2) Manhole RS No. 9 had a narrow opening area due to several floor boards set as a countermeasure for air inflow.

(3) Manhole RS No. 10 had a high bending loss in connection pipe to the existing outlet.

【Countermeasures】

Considering each point of view ((1) to (3)), countermeasures were devised.

(1) Remodeling RS No. 2 manhole

RS No. 2 had a high head loss (3.4 m) which influenced RS No. 1 located upstream. The lowest level of RS No. 2 had a smaller diameter than the upper levels, and the opening area was narrowed by shelf. Therefore, the countermeasure was to remove the shelf from the lowest level to widen the opening area (**Fig. 4**).

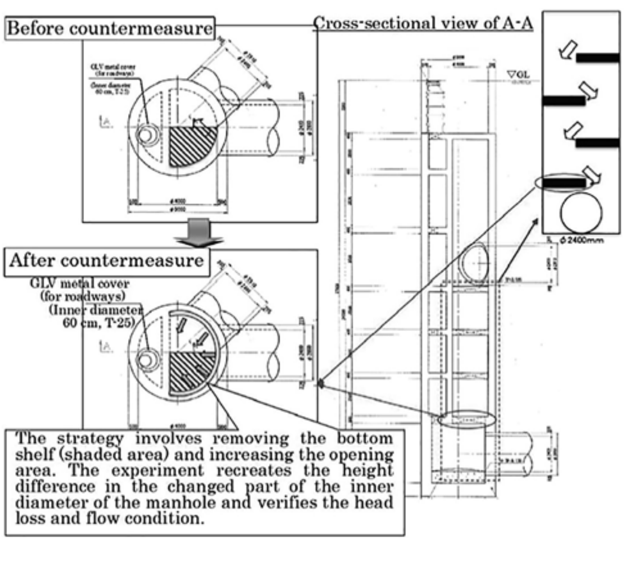

Fig. 4　Countermeasure (RS No. 2)

(2) Remodeling RS No. 9 manhole

In the initially designed facilities, the opening of the RS No. 9 was small and large head loss was observed. To sustain appropriate energy dissipation function and to maximize opening area, opening area was expanded to same area of shelf. Also, when the RS No. 9 manhole's water level increased, the flow was mitigated to maintenance area (**Fig. 5**).

(3) Remodeling the RS No. 10 manhole

The entire RS No. 10 manhole was not fully used as flow area due to the installation of drainage pumps in it. Therefore, the design was changed to increase the bending angle of the connection pipe outflow from the RS No. 10. Also, to reduce head loss, flow deflectors were installed at the bottom and the top of the edge-shaped bending section in the manhole (**Fig. 6**). A flow deflector was a structure to adjust flow.

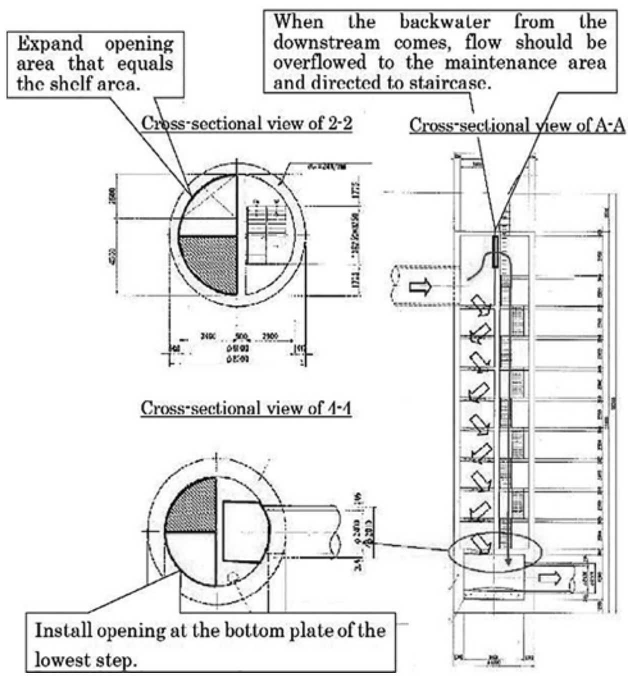

Fig. 5　Countermeasure (RS No. 9)

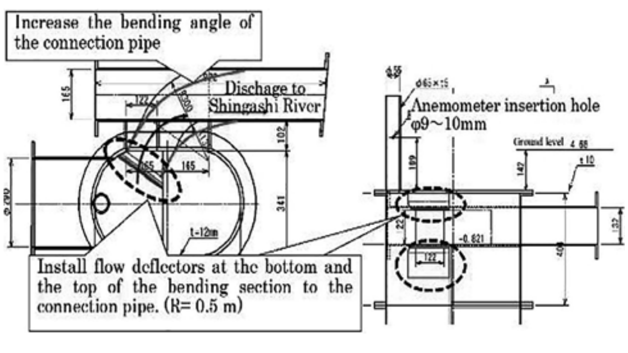

Fig. 6　Countermeasure (RS No. 10)

7. Verification of the effect of the countermeasures and decision on the optimal facilities

7.1 Verification of the countermeasures' effect using "hydraulic model experiments on the facilities with the countermeasures (Step 1)"

Table 3 shows the results of the experiments after implementing the countermeasures (difference between hydraulic level and ground level).

After remodeling the manholes, the target hydraulic level was achieved in case 3 except for the RS No. 5 and No. 10. At RS No. 5 and No. 10, even after improving structural issues, hydraulic level did not achieve GL −1.0 m in case 2. The suspected cause was lack of flow capacity of the sewer down-flow from the relief sewers. When the current discharge regulation to the river is lifted in the future, discharge pipe which satisfy discharge flow rate will be constructed.

7.2 Decision on the optimal facilities "hydraulic model experiments on the optimal facilities (Step 2)"

To achieve target hydraulic level that was 1.0-m lower than ground level, flow rate was further reduced to evaluate the optimal facilities. **Table 4** shows the results of the hydraulic model experiments (difference between hydraulic level and ground level).

RS No. 10 did not achieve the target hydraulic level because the ground level was too low; however, hydraulic level at RS No. 10 was lower than ground level. From these results, RS No. 10 was decided to be satisfactory.

Reducing the flow rate by 0.9 m^3/s additionally at RS No. 5 lowered the hydraulic level lower than GL-1.0-m. Thus, additional flow rate reduction by 0.9 m^3/s needed to be assured to have the optimal facilities.

Table 3 Difference between hydraulic level and ground level (m) (facilities with countermeasures implemented)

Pipeline	Measurement Point	Ground Level (m)	Planned Flow Rate (m^3/s)	Reduced Flow Rate (m^3/s)	Case1 (m)	Case2 (m)	Case3 (m)
Akabane-Nishi major branch sewer 【A】	RS No. 1	10.520	7.059	7.059	−3.647	0.082	−1.517
	RS No. 2	17.000	—	—	−12.774	−7.076	−8.536
Akabane-Nishi major branch sewer 【B】	RS No. 5	6.050	4.902	1.698	−1.052	1.083	−0.959
Akabanedai-San major branch sewer 【C】	RS No. 1 (M3)	8.390	5.887	5.231	−2.747	−0.836	−3.141
	RS No. 6	8.140	0.925	0.088	−2.997	−1.377	−3.132
	RS No. 9	6.430	—	—	−1.355	0.230	−1.361
Akabanedai-Ichi/Iwabuchi-Machi major branch sewer 【D】	RS No. 4	20.800	3.718	3.751	−16.334	−14.197	−15.542
	RS No. 7-1	8.550	1.742	0.122	−4.126	−1.795	−3.763
	RS No. 10	4.680	—	—	−0.530	1.033	−0.074

□ : Lower than GL-1.0 m □ : Between GL-1.0 and GL ■ : Higher than GL

Table 4 Difference between hydraulic level and ground level (optimal facilities)

Pipeline	Measurement Point	Ground Level (m)	50 mm/h constant precipitation (flow rate reduction + additional flow rate reduction at RS No. 5 (0.9?/s))	
			Flow Rate (m^3/s)	Difference between hydraulic level and ground level (m)
Akabane-Nishi major branch sewer 【A】	RS No. 1	10.520	7.059	−3.264
	RS No. 2	17.000	—	−10.414
Akabane-Nishi major branch sewer 【B】	RS No. 5	6.050	0.798	−1.189
Akabanedai-San major branch sewer 【C】	RS No. 1 (M3)	8.390	5.231	−3.428
	RS No. 6	8.140	0.088	−3.460
	RS No. 9	6.430	—	−2.468
Akabanedai-Ichi/Iwabuchi-Machi major branch sewer 【D】	RS No. 4	20.800	3.751	−16.026
	RS No. 7-1	8.550	0.122	−3.911
	RS No. 10	4.680	—	−0.156

□ : Lower than GL-1.0 m □ : Between GL-1.0 and GL ■ : Higher than GL

8. Conclusion

This study confirmed following results,

1）Hydraulic characteristics of the facilities which was long and complex inverted siphon was clarified.
2）Effective countermeasures for residual air gushing and to restrict rising of dynamic water level were presented.
3）The fact that countermeasure facilities for air gushing affected dynamic water level in which low ground level existed in a part of the pipe route was clarified.
4）Countermeasures to reduce head loss in a manhole could be applied to other practices.

These results will be useful for future facility design.

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赤羽西幹線の水理模型実験
―― 長大伏越管の複雑な水理現象に係る課題と対策案に向けた研究 ――

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概　要

長大な伏越管では，複雑で非定常な水理現象を起こすことにより，マンホールからの雨水の溢水やマンホール蓋の飛散等の危険がある。本研究では，水理模型実験により，通常の施設設計での伏越管内の雨水の流れや空気の挙動を確認する。この結果を踏まえ，最小限の施設改造により動水位を低減させ，雨水の溢水等が起こらないような施設設計に改良するための対策を検討し，その効果を実験により確かめた。

キーワード：長大伏越管，高落差，複雑な水理現象，水理模型実験