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An Experimental Study on Characteristics of Hydraulic Stability in Shinwol Rainwater Storage and Drainage System by Continuous Flood and Air Inflow

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Abstract

The rainwater storage and drainage tunnel system is a large-scale urban flood-exclusion facility installed underground to reinforce the insufficient drainage network capability of the metropolitan city and is a facility in the form of an inverted siphon pipeline. “Shinwol rainwater storage and drainage system” such as inverted siphon have many hydraulic instability problems by inlet air. The Shinwol rainwater and drainage system constructed in Gangseo-gu and Yangcheon-gu, Seoul, Republic of Korea, is the first flood control structure in Korea using a deep storage and drainage tunnel system. In this study, hydraulic model experiments were carried out to evaluate the hydraulic stability of the deep storage and drainage tunnel system for variable flood inflow. This study evaluates overflow or non-overflow at drop shafts and analyzes overflow type at overflow occurred scenarios. Experiments formed for 55 scenarios, of which 19 scenarios occurred overflow. Undular bore generated downstream pushes out the pressurized air collected in the facility while moving upstream. In the process, an explosion phenomenon of pressurized air occurs. In addition, after the pressurized air in the pipe is discharged, the phenomenon of stable flood inflow and exhaust occurs, and the facility becomes hydraulic stable.

Keywords: Hydraulic stability; Shinwol rainwater storage and drainage tunnel system; Continuous; Flood; Air

1. INTRODUCTION

Due to recent climate change and urban development, rainfall characteristics and flood patterns are occurring differently than in the past. Looking at recent rainfall characteristics and flood aspects, urban floods frequently occur in large cities due to rainfall characteristics such as short-term heavy rainfall, reduced arrival time due to urbanization, and insufficient penetration capacity, resulting in human life and property damage has occurred. There are several ways to prevent such urban floods, and countries such as the United States, Japan, and Singapore use deep tunnel systems to prevent floods. In the Republic of Korea, where the population is concentrated in large cities, the interest and need for a deep tunnel system have increased since the middle of 2000. In 2013, for the first time in Korea, the construction of the “Shinwol rainwater storage and drainage system” began in Gangseo-gu and Yangcheon-gu, Seoul, and is currently in operation in 2022.

Most of the tunnel systems, such as the Shinwol rainwater storage and drainage system, classify or branch floods in river channels into deep tunnel systems and discharge them into the ocean, lakes, and other rivers. But in the case of the Shinwol rainwater storage and drainage system, rainwater from Gangseo-gu and Yangcheon-gu in Seoul flows into the deep tunnel system to directly exclude floods into Anyang-cheon(river).

Deep tunnel systems, such as the Shinwol rainwater storage and drainage system, have an inverted siphon structure, and as floods flow in, the flow in the system is converted from the initial open channel flow to the pipe channel flow after the full pipe. At this time, it is very difficult to plan and operate systems due to pressurized air in the system and undular bores.

The deep tunnel system is shown in Figure 1. As shown in 1, it can be divided into an inlet facility, an induction tunnel, the main tunnel, an exhaust facility, and an outlet facility. According to the function and utilization of the deep tunnel system, drainage facilities can be divided into natural drainage, induction drainage.

The deep tunnel system has flood flow in the flow in the system is converted from the initial open channel flow to the pipe channel flow after the full pipe. It has the shape of an inverted siphon that flood flows down due to the difference in hydraulic gradient between the upstream and the downstream in the full pipe state. So the design and operation of the system are very difficult. From the initial flood inlet stage to the final flood drainage stage, pressurized air or undular bore has to hinder hydraulic stability. First, looking at the pressurized air, the air introduced with the flood cannot be exhausted to the outside, but is collected in the tunnel and becomes pressurized, and moves upstream along with the undular bore generated downstream. At the time, the air is exhausted to the inlet facility located upstream and a pressurized air explosion may occur. In this study, the hydraulic stability characteristics of the Shinwol rainwater storage and drainage system in various flood scenarios were analyzed and evaluated through a hydraulic model experiment.

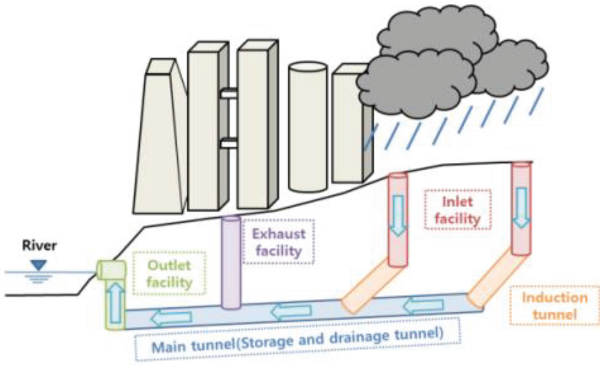
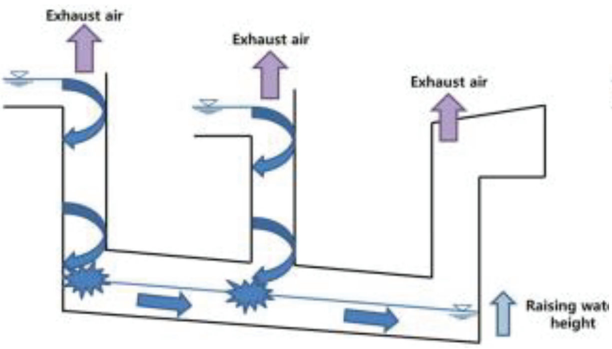


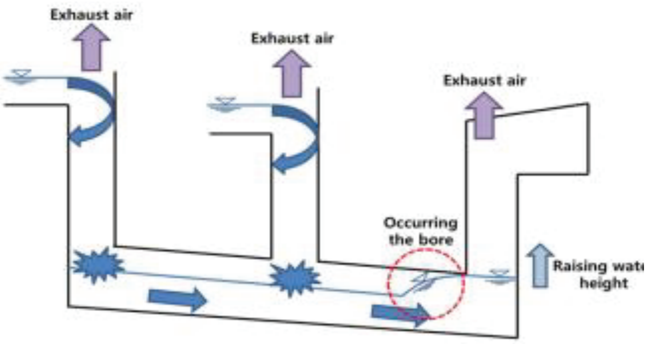
Figure 1. Facilities of deep tunnel system (Oh, et al., 2019)

2. THEORETICAL BACKGROUND

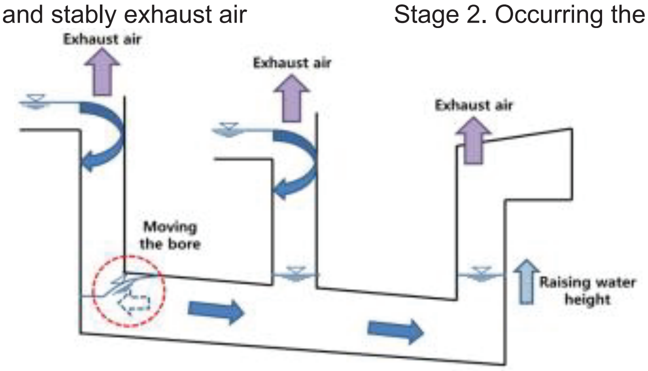
Kushiyma et al. (2003) show the flow in inverted siphon pipelines such as deep tunnel systems as shown in figure 2, it was divided into 5 stages. In the first stage, due to the continuous inflow of floods, becomes full pipe from downstream to upstream of the deep tunnel system. In the second stage, the undular bores are generated downstream due to continuous flood inflow and the air trapped in the tunnel is pressurized without being exhausted. In the third stage, as the undular bore moves upstream, the pressurized air collected in the tunnel is exhausted to the upstream inlet or exhaust facility. In the fourth stage, the pressurized air exhausted in the third stage explodes and blocks the inflow of the flood, causing the overflow. In the fifth stage, stable drainage is achieved due to the stabilization of pressure and energy in the tunnel.



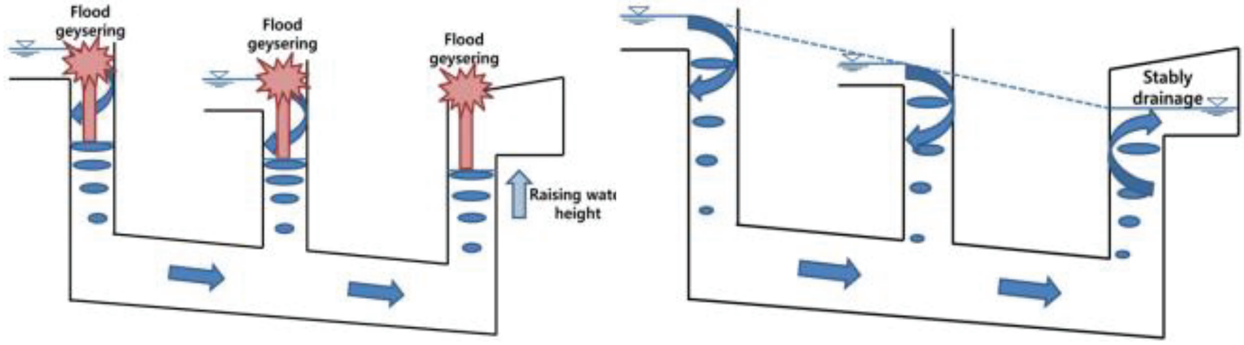
Stage 1. Inflow flood and stably exhaust air



Stage 2. Occurring the bore at downstream



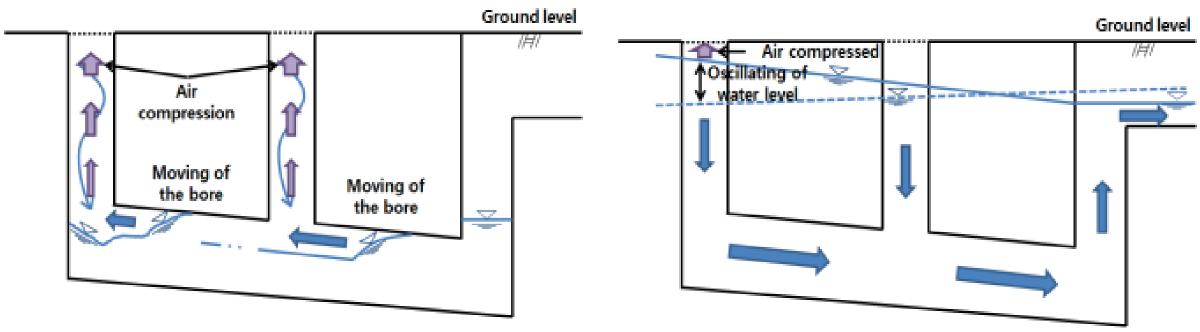
Stage 3. Moving the bore upstream and pressurized to air in the tunnel



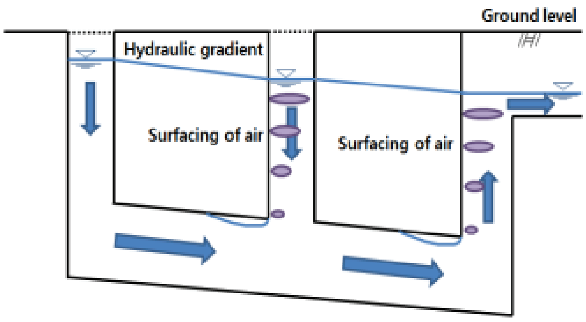
Stage 4. Flood geyser by floating pressurized air Stage 5. Surging and stably drainage

Figure 2. Flow mechanism in deep tunnel system (Kushiyama et al., 2003)

Takanishi and Abe (2006) presented the problem caused by air in the inverted siphon type in the following figure 3, which was divided into three mechanisms. The first is the explosion of pressurized air due to undular bore, the second is oscillation and exhaust of pressurized air, and the third is overflow by air surfacing. Looking at the first, this is a phenomenon that occurs between the third and fourth stages of the flow of the five stages classified by Kushiyama et al. (2003). The air, which was introduced with the flood and could not be exhausted, remained in the tunnel from the upstream to the downstream due to the continuous inflow of the flood, resulting in collection and pressurized. In addition, the pressurized air explosion phenomenon occurs in the process of collecting undular bores generated downstream, moving pressurized air masses upstream, and exhausting them to an inlet or exhaust facility located upstream. At this time, in the process of exhausting the pressurized air, the volume increases according to Boyle's law, and flood inflow is blocked. The second is oscillation and pressurized air exhaust, which is a phenomenon that occurs between stages fourth and fifth of the five stages classified by Kushiyama et al. (2003). Occurs when the flow in the tunnel is converted from the initial open channel flow to the pipe channel flow. At this time oscillation occurs for energy stabilization in the tunnel. The third is an overflow caused by air surfacing, which occurs between stages fourth and fifth of the five stages classified by Kushiyama et al. (2003). Some air masses collected in the tunnel rise and increase in volume in the process of being exhausted, temporarily blocking the inflow of floods or causing small-scale explosions of air masses and overflow.



(a) Explosion of pressurized air by bore (b) Exhaust of pressurized air and oscillation



(c) Overflow by air surfacing

Figure 3. Occurred problem at deep tunnel system by inlet air (Takanishi and Abe, 2006)

3. HYDRAULIC MODEL EXPERIMENTAL

3.1 Shinwol Rainwater Storage and Drainage System

The Shinwol rainwater storage and drainage system, which is the original model of the hydraulic model experiments conducted in this study, was planned and installed in the Gangseo-gu and Yangcheon-gu areas of Seoul where inundation damage occurred due to the heavy rainfall in 2010 and currently operating. In the case of Gangseo-gu and Yangcheon-gu, it is a densely populated area of houses and stores, and large-scale sewer expansion construction was not possible due to underground obstacles (communication, electricity, gas, etc.), so rainwater storage and drainage system were used as a flood prevention measure. The outline of the Shinwol rainwater storage and drainage system is shown in Figure 4.

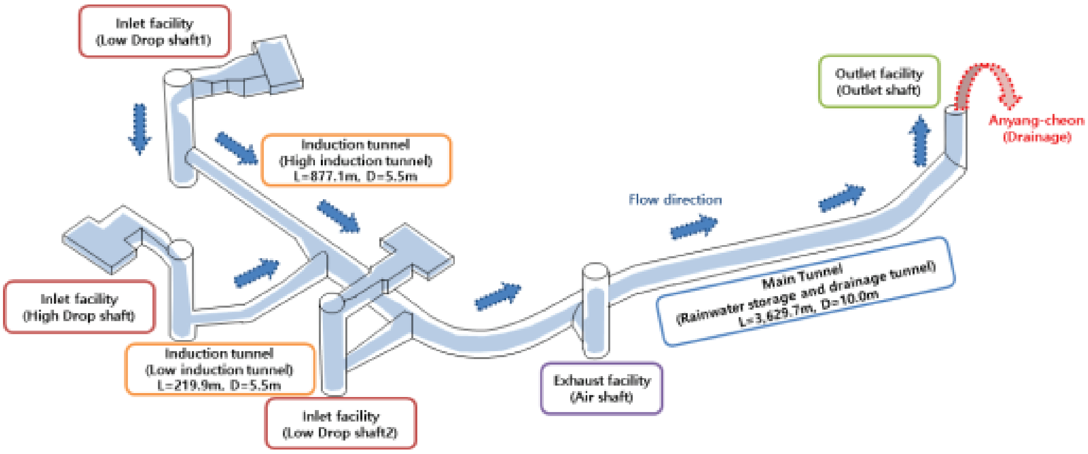


Figure 4. Concept of construction for the Shinwol rainwater storage and drainage system (Hyundai Construction and Engineering).

Details of the Shinwol rainwater storage and drainage system, which is the original model of the hydraulic model experiments conducted in the study as shown in Table 1, there are there inlet drop shafts (Inlet facilities), one air shaft (Exhaust facility), and one outlet shaft (Outlet facility). The total length of the Shinwol rainwater storage and drainage system is about 4.5km including the induction tunnel and the main tunnel, with each inlet drop shaft and exhaust shaft diameter of 5.4m and the amount of volume is 347,778m^3. The disaster prevention performance target of the Shinwol rainwater storage and drainage system is 50 years frequency of Seoul (100mm/1hr).

Table 1. Design conditions for experimental data of each part (Oh, 2019)

Design condition			Data	
			Original (m)	**Model (m)**
Induction tunnel	**Low induction tunnel**	**Diameter (D)**	887.1	17.74
		Length (L)	5.5	0.11
	High induction tunnel	**Diameter (D)**	219.9	4.40
		Length (L)	5.5	0.11
Main tunnel (Storage and drainage tunnel)		**Diameter (D)**	10.0	0.20
		Length (L)	3,629.7	72.59
Inlet facility	**Inlet shaft1 (LDS1)**	**Diameter (D)**	5.4	0.11
		Height (H)	46.2	0.92
	Inlet shaft2 (LDS2)	**Diameter (D)**	5.4	0.11
		Height (H)	45.8	0.92
	Inlet shaft3 (HDS)	**Diameter (D)**	5.4	0.11
		Height (H)	47.6	0.95
Exhaust facility	**Air shaft**	**Diameter (D)**	5.4	0.11
		Height (H)	42.3	0.85
Outlet facility	**Outlet shaft**	**Diameter (D)**	7.5	0.15
		Height (H)	39.8	0.80

3.2 Outline of Hydraulic Model Experimental

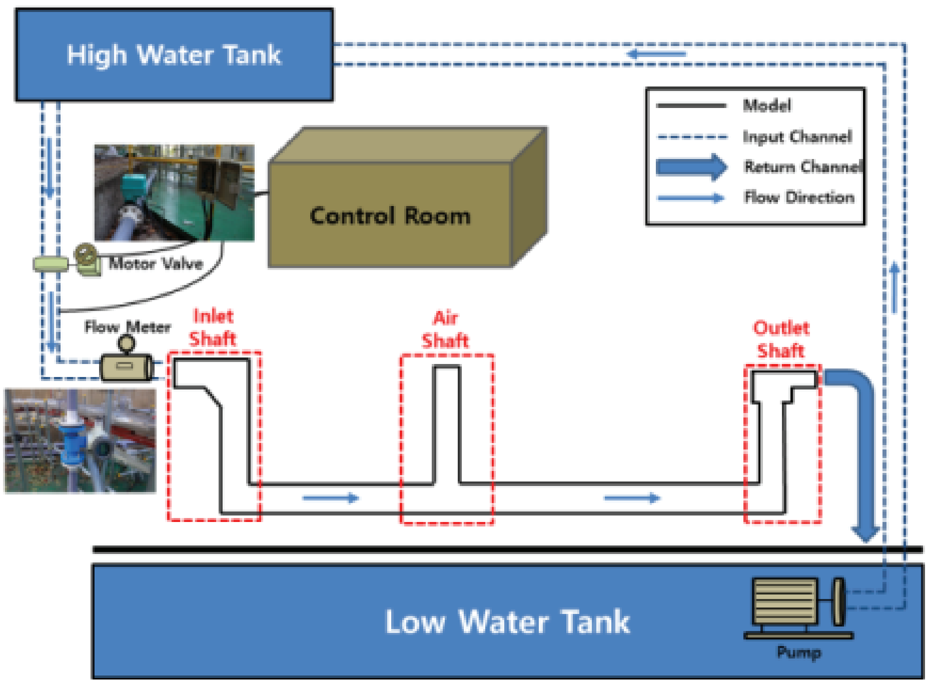
The flow of the Shinwol rainwater storage and drainage system in this study is converted from the initial open channel flow to the pipe channel flow after the full pipe. For this reason, both gravity and viscous forces must be considered in the hydraulic model experimental. However, since it is impossible to match both Froude's law of similarity considering gravity and Reynolds's law of similarity considering viscous force, similarity to viscous force was maintained by adjusting the roughness under the assumption that Manning's average flow velocity was applied in the model. The scale applied in this study is 1/50, and the conversion ratio of each physical quantity according to Froude's law of similarity is shown in Table 2.

Table 2. Scales for each variable of Froude similarity (Oh, 2019)

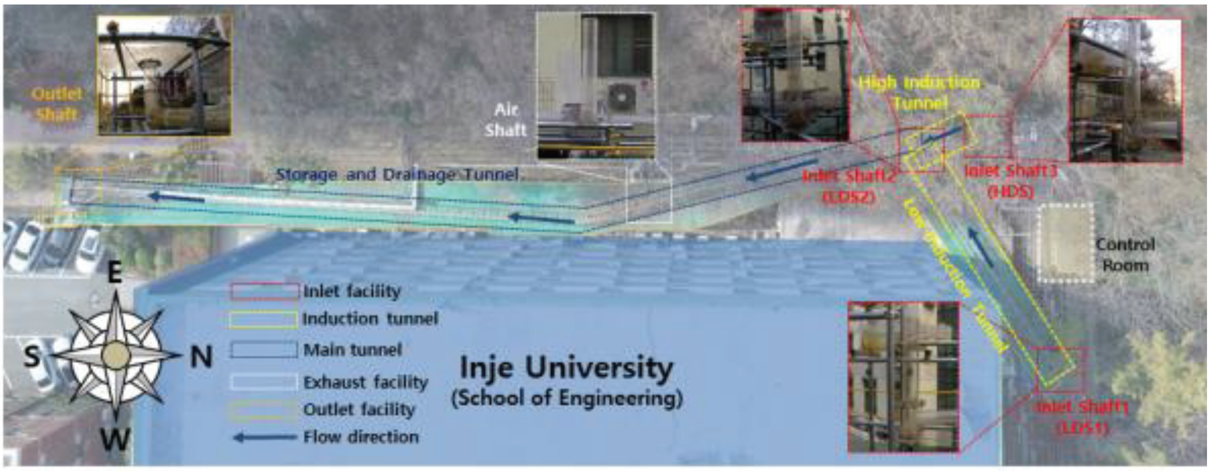
Variables	Froude similarity	Scale
Length	L_r	1/50
Area	L_r^2	1/2,500
Volume	L_r^3	1/125,000
Time	$L_r^{1/2}$	1/7.07
Velocity	$L_r^{1/2}$	1/7.07
Flow rate	$L_r^{5/2}$	1/17,677
Pressure	L_r	1/50
Manning' n	$L_r^{1/6}$	1/1.92

3.3 Experimental Method and Scenarios

The flow cycle of the hydraulic model experiments performed in this study is shown in Figure 5(a). The water stored in the low water tank is sent to the high water tank using a pump, and then water is supplied to each inlet shaft using a motor valve regulator set up in the control room. Water flowing into the inlet shaft has a flow cycle in which it passes through the induction tunnel, the main tunnel, the outlet shaft, and flows back into the low water tank.



(a) Flow cycle in experimental



(b) Experimental setup

Figure 5. System of flow cycle experimental (Oh et al. 2020)

In this study, the experimental model was manufactured using poly-carbonate according to the scale in Table 2 and the model was installed as shown in Figure 5(b). In addition, to evaluate the roughness coefficient of the model, pressure meters were installed at major points such as junctions, curves, and outlets, and the hydraulic gradient was calculated using the distance and pressure of each pressure measurement point. As a result, the roughness coefficient of the model was evaluated to be 0.0086, which was slightly higher than the roughness coefficient of the original model of 0.0080. When using the distortion model in consideration of the roughness coefficient, the pipe diameter scale 1/50 and the length scale 1/71 must be applied, but in the distortion model, the hydraulic characteristics and influence evaluation on the air entrainment in the pipe are not evaluated. So this study applied the normal model.

To embody various flood scenarios, the hydraulic model experimental conditions or scenarios in this study were divided into two major categories, inlet flow amount and residual amount in the tunnel, as shown in Table 3. The inlet flow amount conditions are the 50 years frequency of flooding in Seoul(P50), which is the disaster prevention performance target of the Shinwol rainwater storage and drainage system, 90% of P50 (P30), 80% of P50 (P20), 70% of P50 (P10), 60% of P50 (P5). Residual amount conditions are a total of 11, increasing by 10% from 0% to 100% of the storage capacity of the Shinwol rainwater storage and drainage system. Experimental was performed on 55 scenarios in which inlet and residual conditions were mixed. In addition, in each experiment, the inflow rate of each inlet shaft was changed at 1-minute intervals according to the previously prepared hydrologic curve and the experiment was performed under unsteady states.

This study, investigates the hydraulic stability characteristics of the Shinwol rainwater storage and drainage system to analyze the real-time pressure and undular bores movement characteristics.

Table 3. Detailed conditions for each experimental scenario (Oh, 2019)

Scenario Name	Inlet flow amount (A)			Residual amount in the tunnel (B)			$(A)+(B)/2.78m^3$ (Ratio of the total amount of storage capacity)
	Condition	Name	The total inlet flow amount (m^3)	Condition	Name	Total amount (m^3)	
P50-R0	100% of 100mm/1hr (50yrs. Frequency of Seoul)	P50	2.78	0%	R0	0.00	1.0
P50-R10				10%	R10	0.28	1.1
P50-R20				20%	R20	0.56	1.2
P50-R30				30%	R30	0.83	1.3
P50-R40				40%	R40	1.11	1.4
P50-R50				50%	R50	1.39	1.5
P50-R60				60%	R60	1.67	1.6
P50-R70				70%	R70	1.95	1.7
P50-R80				80%	R80	2.22	1.8
P50-R90				90%	R90	2.50	1.9
P50-R100				100%	R100	2.78	2.0
P30-R0	90% of 100mm/1hr	P30	2.50	0%	R0	0.00	0.9
P30-R10				10%	R10	0.28	1.0

Scenario Name	Inlet flow amount (A) Condition	Name	The total inlet flow amount (m^3)	Residual amount in the tunnel (B) Condition	Name	Total amount (m^3)	(A)+(B)/2.78m^3 (Ratio of the total amount of storage capacity)
P30-R20	(30yrs. Frequency of Seoul)			20%	R20	0.56	1.1
P30-R30				30%	R30	0.83	1.2
P30-R40				40%	R40	1.11	1.3
P30-R50				50%	R50	1.39	1.4
P30-R60				60%	R60	1.67	1.5
P30-R70				70%	R70	1.95	1.6
P30-R80				80%	R80	2.22	1.7
P30-R90				90%	R90	2.50	1.8
P30-R100				100%	R100	2.78	1.9
P20-R0	80% of 100mm/1hr (20yrs. Frequency of Seoul)	P20	2.22	0%	R0	0.00	0.8
P20-R10				10%	R10	0.28	0.9
P20-R20				20%	R20	0.56	1.0
P20-R30				30%	R30	0.83	1.1
P20-R40				40%	R40	1.11	1.2
P20-R50				50%	R50	1.39	1.3
P20-R60				60%	R60	1.67	1.4
P20-R70				70%	R70	1.95	1.5
P20-R80				80%	R80	2.22	1.6
P20-R90				90%	R90	2.50	1.7
P20-R100				100%	R100	2.78	1.8
P10-R0	70% of 100mm/1hr (10yrs. Frequency of Seoul)	P10	1.95	0%	R0	0.00	0.7
P10-R10				10%	R10	0.28	0.8
P10-R20				20%	R20	0.56	0.9
P10-R30				30%	R30	0.83	1.0
P10-R40				40%	R40	1.11	1.1
P10-R50				50%	R50	1.39	1.2
P10-R60				60%	R60	1.67	1.3
P10-R70				70%	R70	1.95	1.4
P10-R80				80%	R80	2.22	1.5
P10-R90				90%	R90	2.50	1.6
P10-R100				100%	R100	2.78	1.7
P5-R0	60% of 100mm/1hr (5yrs. Frequency of Seoul)	P5	1.67	0%	R0	0.00	0.6
P5-R10				10%	R10	0.28	0.7
P5-R20				20%	R20	0.56	0.8
P5-R30				30%	R30	0.83	0.9
P5-R40				40%	R40	1.11	1.0
P5-R50				50%	R50	1.39	1.1
P5-R60				60%	R60	1.67	1.2
P5-R70				70%	R70	1.95	1.3
P5-R80				80%	R80	2.22	1.4
P5-R90				90%	R90	2.50	1.5
P5-R100				100%	R100	2.78	1.6

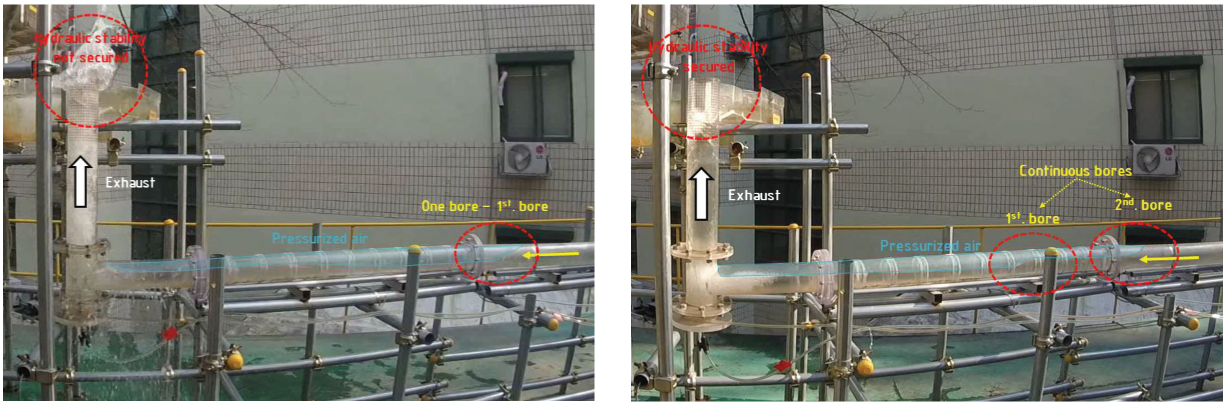
4. EXPERIMENTAL RESULTS

In this study, the effect of pressurized air and undular bores on the Shinwol rainwater storage and drainage system in various flood scenarios was investigated through a hydraulic model experiment, and the results are shown in Table 4. In table 4, hydraulic stability secured or not was evaluated as not securing the hydraulic stability of the facility if overflow occurred in even one of the three inlet shafts and one air shaft. In this study, overflow occurred in LDS1 in all scenarios where hydraulic stability was not secured. When overflow did not occur and the flood flowed and drained stably, it was indicated as freeboard. Although overflow did not occur, when the water level rose to the top of the shaft during the energy stabilization, it was expressed as a full shaft. If the total amount of inflow (inflow amount + residual amount) of the scenario is smaller than the storage capacity of the Shinwol rainwater storage and drainage system, the drainage function cannot be operated and only the storage function operates, so it is expressed as only storage.

Table 4. Experimental results at each part (Oh and Jun, 2021)

Scenario Name	The overflow occurred or not at each shaft				Hydraulic stability(H.S.) secured or not	Type of overflow
	Inlet shaft1 (LDS1)	Inlet shaft1 (LDS2)	Inlet shaft3 (HDS)	Air shaft		
P50-R0	Freeboard	Freeboard	Freeboard	Freeboard	Secured H.S.	-
P50-R10	Overflow	Overflow	Freeboard	Freeboard	Not secured	
P50-R20	Overflow	Overflow	Freeboard	Freeboard	Not secured	Air explosion
P50-R30	Overflow	Overflow	Freeboard	Freeboard	Not secured	Air explosion
P50-R40	Overflow	Overflow	Freeboard	Freeboard	Not secured	Air explosion
P50-R50	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P50-R60	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P50-R70	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P50-R80	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P50-R90	Exist freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P50-R100	Exist freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P30-R0	Only storage	Only storage	Only storage	Only storage	-	-
P30-R10	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P30-R20	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P30-R30	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P30-R40	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P30-R50	Overflow	Overflow	Freeboard	Freeboard	Not secured	Air explosion
P30-R60	Overflow	Overflow	Freeboard	Freeboard	Not secured	Air explosion
P30-R70	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P30-R80	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P30-R90	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P30-R100	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P20-R0	Only storage	Only storage	Only storage	Only storage	-	-
P20-R10	Only storage	Only storage	Only storage	Only storage	-	-
P20-R20	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P20-R30	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P20-R40	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P20-R50	Overflow	Full Shaft	Freeboard	Overflow	Not secured	Oscillation
P20-R60	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P20-R70	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Oscillation
P20-R80	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P20-R90	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P20-R100	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P10-R0	Only storage	Only storage	Only storage	Only storage	-	-
P10-R10	Only storage	Only storage	Only storage	Only storage	-	-
P10-R20	Only storage	Only storage	Only storage	Only storage	-	-
P10-R30	Only storage	Only storage	Only storage	Only storage	-	-
P10-R40	Freeboard	Freeboard	Freeboard	Freeboard	Secured	
P10-R50	Freeboard	Freeboard	Freeboard	Freeboard	Secured	
P10-R60	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Oscillation
P10-R70	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Air explosion
P10-R80	Overflow	Freeboard	Freeboard	Freeboard	Not secured	Oscillation
P10-R90	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P10-R100	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P5-R0	Only storage	Only storage	Only storage	Only storage	-	-
P5-R10	Only storage	Only storage	Only storage	Only storage	-	-

Scenario Name	The overflow occurred or not at each shaft				Hydraulic stability(H.S.) secured or not	Type of overflow
	Inlet shaft1 (LDS1)	Inlet shaft1 (LDS2)	Inlet shaft3 (HDS)	Air shaft		
P5-R20	Only storage	Only storage	Only storage	Only storage	-	-
P5-R30	Only storage	Only storage	Only storage	Only storage	-	-
P5-R40	Only storage	Only storage	Only storage	Only storage	-	-
P5-R50	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P5-R60	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P5-R70	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P5-R80	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P5-R90	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-
P5-R100	Freeboard	Freeboard	Freeboard	Freeboard	Secured	-



(a) Pressurized air of the non-stable exhaust (b) Pressurized air of the stable exhaust

Figure 6. Hydraulic stability at LDS1 by undular bore

As shown in Table 4, in the inflow scenarios of P50, P30, P20, and P10, it was analyzed that hydraulic stability was not secured when the total inflow amount compared to the storage capacity of the tunnel was 1.3 ~ 1.5. This was analyzed to be effective for securing hydraulic stability to maintain and operate the residual amount of the tunnel at 30 % or less if rainfall of P10 or higher is predicted for the stable operation of the tunnel in the future.

When analyzing the recorded videos, it was analyzed that hydraulic stability was not secured because overflow occurred in 19 of the 55 experimental scenarios as shown in Table 4. Looking at the type of overflow, 15 of the 19 experimental scenarios in which overflow occurred were analyzed to be pressurized air explosions caused by undular bores as shown in Figure 2(a), and 4 experimental scenarios were analyzed to be generated overflow due to oscillation and pressurized air exhaustion as shown in Figure 2(b).

As shown in Table 4 and Figure 6, in the experimental scenario in which hydraulic stability is secured, small-scale undular bores continuously moved upstream, but in the experimental scenario in which hydraulic stability is not secured, large-scale undular bore was analyzed to move upstream alone. When the hydraulic stability is not secured, it was analyzed that the flow rate is temporarily blocked as the pressurized air explodes and the volume of pressurized air increases according to Boyle’s law while the pressurized air in the pipe exhausted through the upstream shafts.

5. CONCLUSIONS

In this study, a hydraulic model experiment was performed to analyze the effect of pressurized air generated in the facility on the hydraulic stability under various flood scenarios (inflow condition, residual water condition) targeting the Shinwol rainwater storage and drainage system.

1) In the inflow amount scenario of P50, P30, P20, and P10, it was analyzed that hydraulic stability was not secured when the total inflow amount was 1.3 to 1.5 compared to the tunnel’s storage capacity. It was analyzed that if rainfall above P10 is predicted for the stable operation of the tunnel in the future, maintaining and operating the residual amount of the tunnel below 30 % is effective in securing hydraulic stability.

2) It was analyzed that hydraulic stability could not be secured due to the occurrence of overflow in 19 of the 55 experimental scenarios. Looking at the type of overflow, 15 of the 19 experimental scenarios in which overflow occurred were analyzed to be pressurized air explosions caused by undular bores, and 4 experimental scenarios were analyzed to cause overflow due to oscillation and pressurized air exhaustion.

3) As a result of the hydraulic model experiment according to the various flood inflow conditions conducted in the study, after the continuous flood inflow filled the tunnel from the downstream, the air introduced with the flood could not be exhausted and the air was in a pressurized state. In addition, as the undular bore generated from the downstream moves upstream, the tunnel moves upstream and exhausts it, causing flood inflow blocking and overflow due to the pressurized air explosion and consequent suffocation of the inlet shafts.

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