Reliability Improvement of Rainwater-Drainage System Using IoT and AI

Ryuichi Sekita, PhD, PE, Fukuyama University
Teppei Watanabe, Nichiatukihan Co., Ltd
Tadashi Yoshizawa, Serial Games Inc.,
Kenta Nakanishi, Nita Consultant Co., Ltd.

Key Words: heavy rainfall, rain forecast, drainage experiments, flood analysis

SUMMARY & CONCLUSIONS

Japanese-government data on the degree of damage by flood type indicates that inland floods cause the highest recorded damage every year, without the occurrence of large-scale damage due to levee breaches. Therefore, research on improving rainwater-drainage systems is important for damage prevention for inland flooding

A conventional rainwater-drainage operation scheme is called "water-level control," where a pump is started-up/stopped when the drainage-water level of the pump-well reaches a given threshold. To prevent inland flooding caused by heavy rain, the drainage-pump operator sometimes manually manipulates the water-level control and starts-up the pump before the rainwater level reaches the threshold. Notably, conventional rainwater-drainage system pumps have never been operated by applying rain-forecast big data, which is one of the factors that make rainwater-drainage systems unreliable. Our research focuses on improving the reliability of an autonomous system using IoT and rain-forecast big data.

This paper describes the design of our improved rainwater-drainage system and discusses the verification results of the system's inland flood-damage prevention through drainage experiments and inland-flood analysis. These verification results show that even an improved system is insufficient for reducing inland flood damage. With further consideration, we suggest that an advanced extreme-heavy-rain prediction system is required. New research is underway to develop an AI system for predicting extremely heavy rainfall. An overview and the plan of the development of this AI system are also discussed.

1 INTRODUCTION

In recent years, floods and landslides have occurred in many cities and towns in Japan, and flood damage caused by heavy rain in the Yamaguchi Prefecture and Tohoku region in July 2023 was severe. The number of short-term heavy-rain events since 1975, based on data published by the Japan Meteorological Agency [1], is shown in Figure 1. The dotted line in the figure indicates the number of occurrences annually, and the increasing trend is clear. If short-term heavy rain exceeds the rainwater-drainage capacity of a town, inland-flood damage will occur. From these data, we can infer that inland-flood damage is increasing. Figure 2 shows the annual amount of damage for each flood type from fiscal year 2010 to 2020 based on data published by the Statistical Bureau of the Ministry of Internal Affairs and Communications of the Japanese government [2]. Every year, inland floods cause the highest amount of damage, unless an external water flood owing to a levee breach causes major damage. Heavy rain, as a natural phenomenon, cannot be prevented; however, external water flooding can be prevented by designing and constructing river embankments with appropriate safety factors. In contrast, the prevention of inland flooding faces technical difficulties because it requires the appropriate design and construction of rainwater-drainage systems as well as water-level adjustment between the pump well and the river or sea to which the water drains. This study focuses on reducing inland-flood damage by improving the reliability of rainwater-drainage systems, which requires technological innovation.

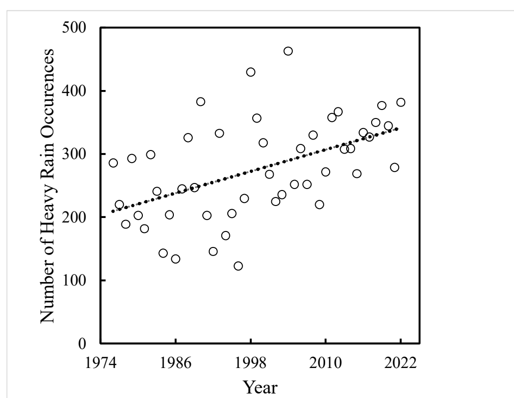

Figure 1 Yearly Number of Short-term Heavy-rain occurrences in Japan

Several studies have been conducted to improve the reliability of rainwater-drainage systems. For example, a robust rainwater-drainage pump that can be driven even if air is sucked into the pump inlet vane [3] and a rainwater-drainage operation

979-8-3503-0769-6/24/$31.00 ©2024 IEEE

system that applies fuzzy control have been proposed. Unfortunately, no practical research has improved the reliability of rainwater-drainage systems, but research results showing that "pump-drainage performance and reliability may be improved if heavy-rain-forecast data is applied to pump operation [4]" should be considered.

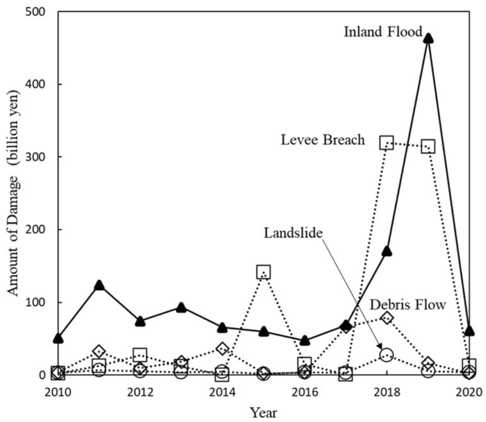

Figure 2 Annual Amount of Damage by Flood Type in Japan

Flood analysis successfully verified the effectiveness of the system improvement in reducing flood damage; therefore, analytical verification has been actively performed. "NILIM2.0[5]" developed by the Ministry of Land, Infrastructure, Transport, and Tourism and "AFREL-SR [6]" developed by Nita Consultants are software that are actively used in Japan to analyze not only external floods, but also inland floods. "NILIM2.0" stopped upgrading in 2012 and is not user-friendly. Therefore, "AFREL-SR" is used in this study.

This study utilizes drainage experiments and inland-flood analysis using "AFREL-SR" to verify the improvement in the reliability of rainwater-drainage systems by introducing rainfall analysis and applying the Internet of Things.

2 DESIGN OF A NEW RAINWATER-DRAINAGE SYSTEM

Nichiatsu Kihan Co., Ltd. obtained a Japanese patent for a new controller, as part of the pump-system design, that can improve the reliability of the drainage system. There was no major change in the pump; however, an external control unit was added to independently input the drive command from the Amazon Web Service (AWS) to the pump controller. The drainage station was equipped with a GPS receiver that identified location information, a wireless router that received drive commands from the rain-cloud radar-analysis computer in the AWS for the control unit, and a data logger that sent the pump data to the AWS. The new rainwater-drainage operation was as follows, and our proposal system's overview was shown in Figure 3.

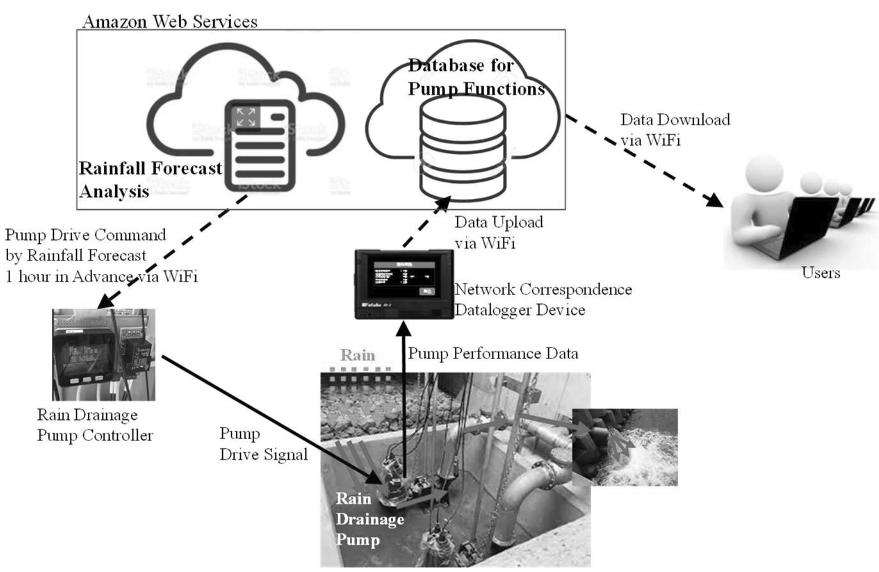

Figure 3 Proposed Rainwater-Drainage System

I) The latitude and longitude of a rainwater-drainage station was determined from a GPS signal.
II) The rainfall forecast for the following 1 h was calculated in the AWS with a 1-km mesh for a 5-km square centered on the rainwater-drainage station. Then, Grid Point Value (GPV) 1-km mesh of the predicted rainfall data was received in the GRIB2 format distributed by the Japan Meteorological Agency every 30 min.
III) When the analytical forecast rainfall exceeded 20 mm/h, a pump start-up command was generated and sent to the rainwater-drainage system via Wi-Fi from the AWS.
IV) Upon receiving the command, the control component in the rainwater-drainage system sent a startup signal to the pump.
V) The pump started draining immediately and stopped when the water level of the rainwater-drainage system decreased to its lowest threshold value.
VI) The data logger in the system collected the receiving time of the pump start-up trigger, pump start-up time, pump stop time, and water-level data driven by sampling every 10 s.

VII) The collected data were sent to a database built into the AWS in real time via Wi-Fi.

VIII) All rainwater-drainage-system officers could observe and download all data from the AWS database at any time to monitor the system status.

3 OVERVIEW OF VERIFICATION TEST FOR NEW SYSTEM

Tests to verify the reliability improvement of the drainage system began in September 2020. Verification tests are difficult to execute on a new drainage-pump system that has no practical use record at any official drainage-pump station because every official pump station is responsible for regional inland-flood prevention. Therefore, system-verification tests were conducted at a shopping-mall parking-lot drainage pump in 2020. Permission was obtained from Fukuyama City Hall in 2021 to install an external control unit at an official drainage-pump station and measure the water level and timing data of the pump-drive signal as a partial verification test. After discussing the 2021 test results with the Water and Sewerage Bureau of Fukuyama City Hall, permission was obtained to execute drainage tests using a test pump at the Haisenchi rainwater-drainage station that manages the Kamaya drainage area in Fukuyama City. The Kamaya drainage area is indicated in green near the Seto Inland Sea along the Ashida River to the south of the JR Fukuyama Station, as shown in Figure 4. This site includes one normal-use pump and one high-pressure pump, which are operated when the pump-well water level approaches a critically high level at the Haisenchi rainwater-drainage station. An additional test pump owned by Nichiatsu Kihan Co., Ltd. was installed at the station on July 28, 2022. Figure 5 shows the temporary setup of the test pump, and Table 1 lists the specifications of the three pumps.

Verification tests at the Haisenchi rainwater-drainage station have been conducted since July 30, 2022. As neither summer seasonal heavy rain nor typhoons approached Fukuyama City in 2022, verification of the effectiveness of the pump driven by rainfall forecasts was insufficient at that time. The long-term durability of the external control unit was verified after more than half a year, but data communication between the external control unit and rainfall-forecast server in the AWS was unstable. Communication was interrupted at 6:00 AM on January 6, 2023, and automatically restored at 1:00 AM on January 8. The external control unit received power from an uninterruptible electrical power supply; therefore, based on past failures, we assumed that this failure was caused by malfunctions of the components in the external control unit. In addition to the abovementioned failures, the test system experienced an unintentional system-off failure every year. Even with the consideration that the external control unit is based on Raspberry Pi and is not completely reliable, the system should not be turned off unintentionally because it is the official inland flood-prevention infrastructure. Thus, improving the equipment reliability of the external control unit to develop a robust system remains an issue.

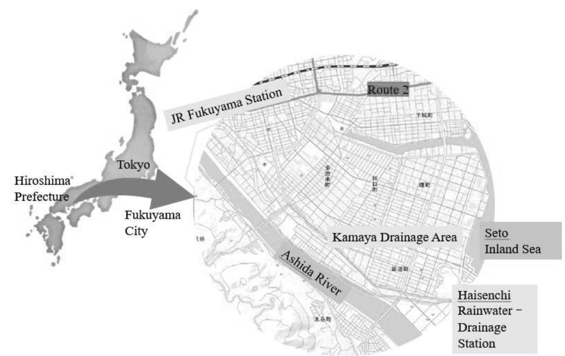

Figure 4 Drainage Test Area: Kamaya Drainage Area

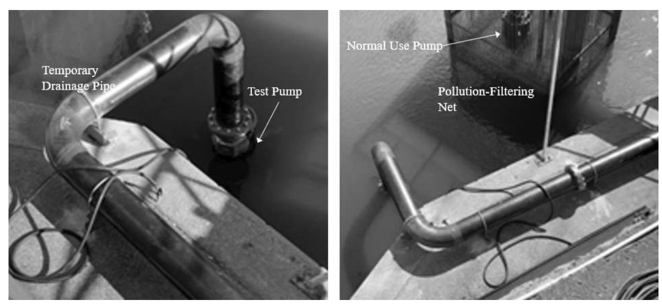

Figure 5 Drainage-Test Configuration

Table 1 Drainage-Test Pump Specifications

	Normal Use Pump	High-Pressure Pump	Test Pump
Manufacturer	Tsurumi Pump	Hitachi, Ltd	Tsurumi Pump
Drainage Volume m^3/min	10	120	4
Draining Start	TP-0.97m, Automatic	TP-0.1m, Manual	Rain Forecast, Automatic
Draining Stop	TP-1.07m, Automatic	TP-0.6m, Automatic	TP-1.15m, Automatic
	TP: Mean Sea-Level of Tokyo Bay（Japan Mean Elevation=0 m）		

4 VALIDITY OF RAINFALL FORECAST

The first step in verifying the reliability improvement of the system was to confirm that the rainfall forecast and actual rainfall amounts were equal. The Minoshima rainfall-observatory station of the Ministry of Land, Infrastructure, Transport, and Tourism is located 1 km south of the Haisenchi rainwater-drainage station. The one-hour rainfall data of the Minoshima rainfall-observatory station published on their website was compared with the rainfall forecast for that hour in the AWS.

The calculation method for the rainfall forecast is explained in Section 2, and we reconfirmed that the calculated value is the accumulated rainfall of 25 blocks of a 5-km square with a 1-km mesh. Rainfall-forecast calculations on the AWS were performed every 30 min, and Serial Games Inc. presented the monthly calculation results at the end of the month.

The following trend was confirmed by comparing the rainfall data at the Minoshima rainfall-observatory station and the rainfall forecast from August 2022 to March 2023.

- The rainfall forecasts on the AWS are so-called "wait-and-see," because forecasts are produced even if no actual rainfall occurs; however, no "oversights" exist in which actual rainfall cannot be predicted.
- Rainfall always occurred at the site when the rainfall-forecast threshold of 20 mm/h for sending drive commands from the AWS was exceeded.

Figure 6 shows the representative data for four days before and after November 23, 2022, when heavy rainfall occurred during the test period. These considerations are as follows:

- The rainfall forecast was relatively good at predicting a situation in which rainfall became stronger.
- One hour after the rainfall forecast on the AWS exceeded the threshold, heavy rain began. Based on this evidence, we can conclude that the rain-forecast system was able to verify heavy rainfall, as designed.

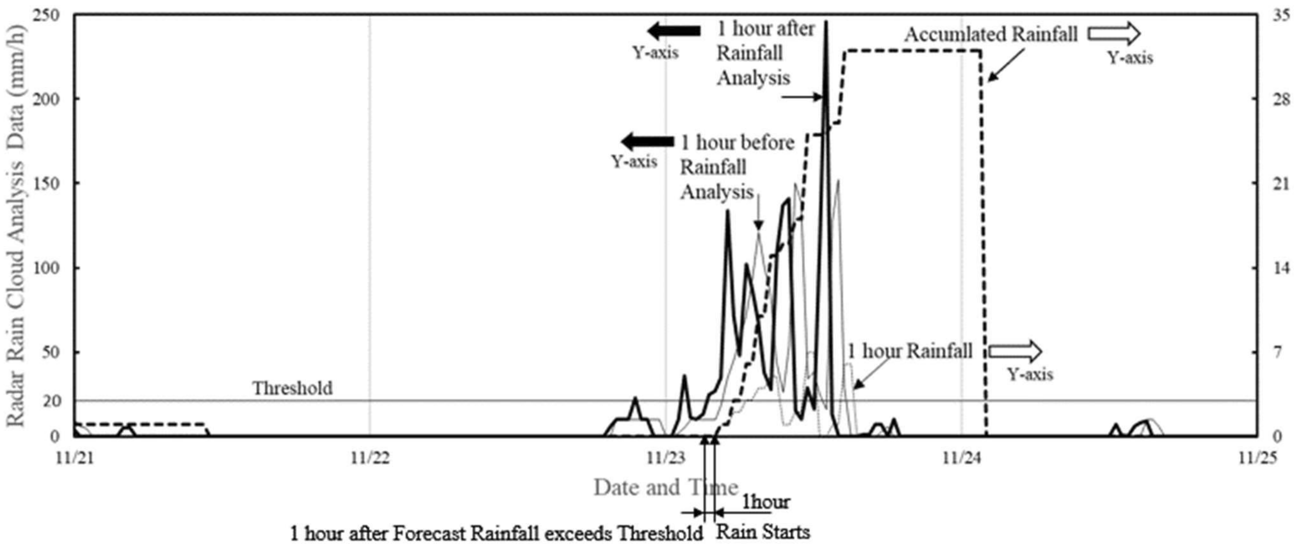

Figure 6 Comparison of Minoshima Rainfall Observatory Data and Radar Rain-Cloud Analysis (Nov.21–24, 2022)

5 RAINWATER-DRAINAGE SYSTEM TESTS

5.1 *Test Data*

Fine Weather: Figure 7 shows the time history of the pump-well water level on November 22 with no rainfall. Even in fine weather, the pump-well water level reached the upper threshold due to the inflow of water from the Kamaya drainage area, and the pump started draining and stopped at the lower level. Thus, water-level-control pumps are necessary during normal times, and the rainfall-forecast system has no effect on the pumps.

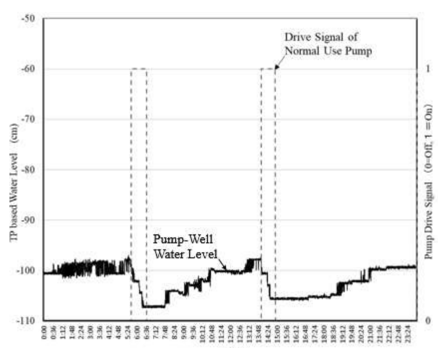

Figure 7 Time History of Pump-Well Water Level (Nov. 22 0:00-23:59)

Normal Rain: Figure 8 shows the time history of the pump-well water level on July 31. At the time when the second drainage of the normal-use pump was completed, the test pump also started drainage based on the drive command from the AWS. The test pump continued to drain water, and the rain-forecast system kept the pump-well water level low.

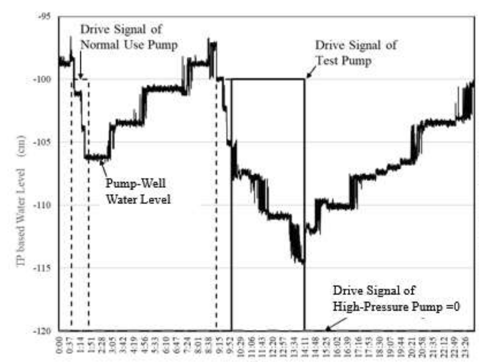

Figure 8 Time History of Pump-Well Water Level (July.31 0:00–23:59)

Heavy Rain: Figure 9 shows the rainfall data and pump-well water level on November 23. The figure shows a pair of upper and lower graphs with respect to time on the x axis. The discussion is presented as follows:

- Three hours after the start of rainfall at 3:20, the normal-use pump started to drain the water, as was set, and one and a half hours later, the test pump was started. As shown in Figure 6, the drive command for the test pump should have been issued at 2:20 from the AWS. Thus, the 5.5-hour timing delay in the rain-forecast system must be resolved.
- Even after the two pumps drained the water, the water level continued to rise owing to heavy rainfall and began to fall only after the rain stopped.
- The test pump was set to stop driving at a water level of TP-1.15m, but stopped at TP-0.95m. Thus, failures may have occurred in the test-pump control system.

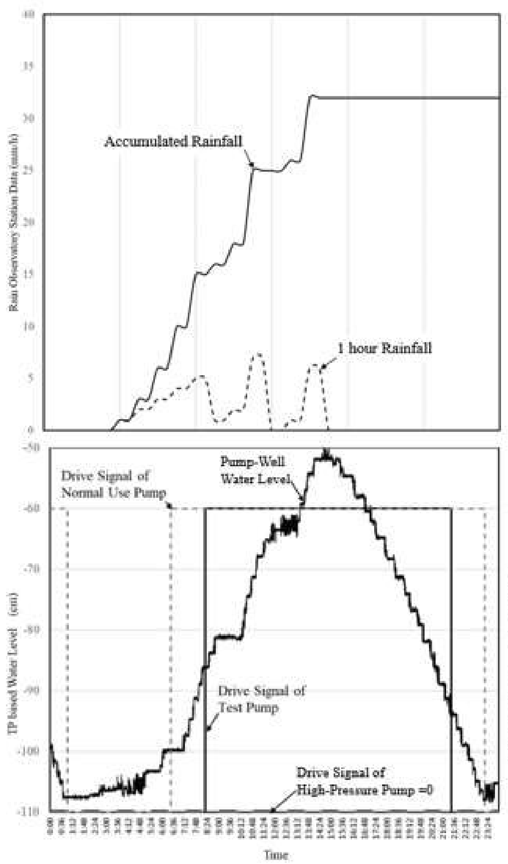

Figure 9 Time History of Rainfall and Pump-Well Water Level (Nov.23 0:00-23:59)

5.2 *System Verification*

The points of the rain-forecast drainage system verified by the drainage-system tests are as follows:

- We verified that rain forecasts on the AWS could be sent to the pump-drive command 1 h before the start of rain. However, the external control unit of the station could not receive repeatable signals.
- The effect of keeping the pump-well water level low by starting the pump drive earlier based on rain forecasts was partially verified. However, in cases where heavy rainfall continued and rainwater inflow exceeded the pump-drainage capacity, the effect was limited.
- Drainage-system test data for extremely heavy rain were not collected during the system test period.
- Thus, verification tests must be continued to improve the reliability of the system.

6. INLAND-FLOOD ANALYSIS

6.1 *Input Data*

Map information of the Kamaya drainage area was downloaded from the Geospatial Information Authority of Japan, and the elevation data were stored in AFREL-SR. Rainfall in the Kamaya drainage area flowed into a small river, which led to the Haisenchi rainwater-drainage station through the gutters. The map information was divided into 1 mesh of 5m square, and the gutter was input to the mesh. In AFREL-SR, all the gutters can be accurately input because the gutters are input only on the edges of the mesh.

Rainfall in Fukuyama City during the test period was not sufficiently heavy to cause inland flooding. On September 18, 2022, Typhoon 14 hit Nobeoka City, Miyazaki and caused an inland flood; thus, the Japan Meteorological Agency AMeDAS rainfall data for that day and location [7] were entered into AFREL-SR.

6.2 *Analysis Model*

The AFREL-SR analysis model comprised a two-dimensional (2D) unsteady flow model for the ground surface, 1D open unsteady flow model for the drainage channel, and 1D pipe unsteady flow model for the drainage channel.

The ground-surface flow was calculated using the equation describing the flow-rate exchange between the channel or drainage pump and the ground. The drainage-channel flow was defined at the center of the computational mesh of the ground layer. Water exchange between the ground and waterways was analyzed using a mesh in which the waterway mesh overlapped with the ground mesh. The Drainage pump was modeled to transmit the flow rate from the point where it was installed to a specified point.

6.3 *Analysis Results*

Analysis was performed for three cases, considering the pump configuration of the Haisenchi rainwater-drainage station.

Case1: Normal-use pump with water-level control.

Case2: Normal-use pump with rain-forecast control.

Case3: High-pressure pump with extreme-rain-forecast control that has not yet been realized.

Inland flooding occurred in both Case1 and Case2. In addition to Case2, Case3 verified the effect of driving the high-pressure pump 1 h before an extremely heavy rain. Case3 assumed that an inland flood would not occur; however, the flood had in fact occurred. Therefore, an analysis of the pump-well water level was added. The results are presented in Figure 10. Starting the high-pressure pump earlier does not prevent flooding owing to the insufficient drainage volume for extremely heavy rain. The effect of the new control was that the pump-well water level rose more slowly than in Case2.

7. RESEARCH FOR EXTREME-HEAVY-RAIN FORECAST

Detecting extremely heavy rain in advance and driving a large-drainage-volume pump before the pump-well water level rises sharply is effective. However, an extreme-heavy-rain detection system has not yet been developed. Therefore, research will be conducted in the next two years to add AI extreme-heavy-rain forecasting to the system, as follows:

- Research of optimal-control theory for the system
- Exploring meteorological parameters
- Application of vertically integrated liquid (VIL)water content data
- Application of geostationary meteorological satellite
- Modeling the parameters with the AI engine “artisoc”

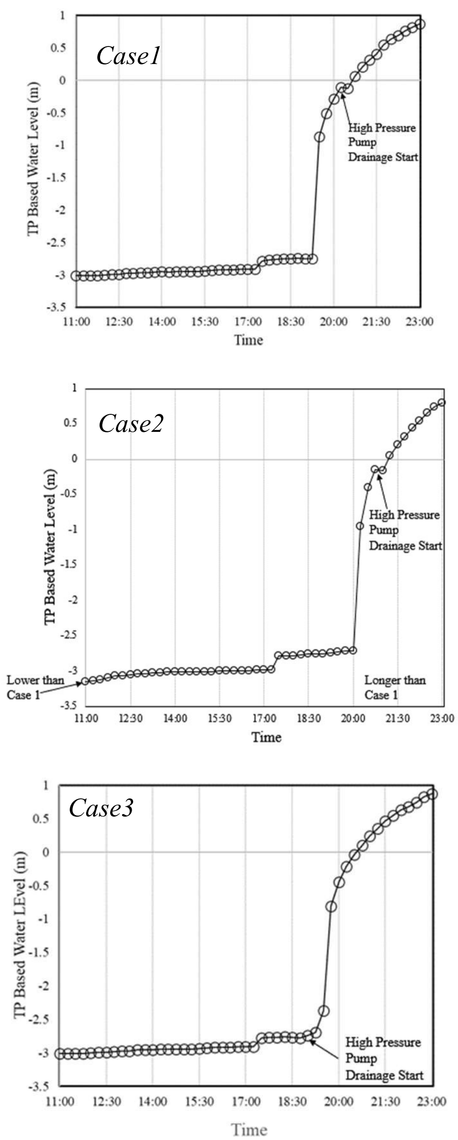

Figure 10 Pump-Well Water Level Analysis Results

8. CONCLUSION

This study partially verified the reliability improvement of rainwater-drainage systems using a new drive-control method with rain forecasts based on the AWS. Issues were identified through tests and analysis. The main issues are as follows:

- AWS rain-forecast prediction delays occurred, and the rainfall threshold should be examined.
- The need to accumulate verification data for heavy rainfall and operation repeatability were recognized.
- Inland-flood analysis showed that rainwater-drainage systems require an extreme-heavy-rain forecast function. Thus, an AI model that can detect extremely heavy rain in advance is necessary.

These results are significant because they can identify issues in the process of improving the reliability of rainwater-drainage systems and they represent the start of activities to reduce the damage caused by inland flooding through industry-government-academia collaboration.

REFERENCES

1. Japan Meteorological Agency, “Changes in extreme phenomena such as heavy rain and extremely hot days,” http://www.data.jma.go.jp/cpdinfo/extreme/extreme_p.html, Last viewed on 10 April 2023.
2. Statistics Bureau, Ministry of Internal Affairs and Communications Japanese Government, “e-star information about Japan in statistics,” https://tokusuru-bosai.jp/refuge/refuge05.html, Last viewed on 10 April 2023.
3. Konishi M., et al., “Pump operable with full speed at any suction water level, 1st Report,” Turbomachinery Society 19(6) 1991, pp 7-12.
4. Shamoto T., et al., “Practical use of a pump control system using fuzzy control,” IEEE Japan Transaction on Industry Application 121(4) 2001, pp 468-475.
5. Ministory of Land, Infrastructure, and Transport, “Manual of urban flooding analysis model (NILIM 2.0),” 1988.
6. Nita Consultant Co., Ltd. Japan, “About AFREL-SR,” http://afrel-s.jp/about/, Last viewed on 30 March 2023.
7. Japan Weather Association, “tenki.jp, Nobeoka,AMeDAS of September 18, 2022,” https://tenki.jp.past/2022/09/18/amedas/9/48/87141.html/, Last viewed on 28 March 2023.

BIOGRAPHIES

Ryuichi Sekita, PhD, PE of Japan
Department of Smart System, Fukuyama University
985-1 Sanzou, Higashimura-cho, Fukuyama City, Hiroshima, 729-0292, Japan

e-mail: sekita@fukuyama-u.ac.jp

Ryuichi Sekita is an associate professor in the Department of Smart System at Fukuyama University. He was previously an associate senior engineer at the Japan Aerospace Exploration Agency (JAXA). He earned his doctoral degree in Systems Management from the University of Tsukuba in 2009. He earned his Master of Science degree in aerospace engineering from the University of Alabama in Huntsville in 1993. He earned his bachelor’s degree in mechanical engineering from Tokyo Metropolitan University in 1983. His research activities are focused on systems engineering for complex systems. He is a member of the AIAA and Reliability Association of Japan.