Research article

Development of an Emergency Discharging Device and an Early Warning System for Floods at Irrigation Ponds

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Abstract The spillways of irrigation ponds in Japan should be repaired to safely pass the 200-year flood event, which is the design criteria set by the government. However, extensive time is required to repair the spillways owing to the large number of ponds and the high repair costs. Therefore, we developed a low-cost early warning system (EWS) to reduce the risk to households in case of floods, as well as a low-cost emergency discharging device (EDD) to prevent or mitigate these floods. The Yutani irrigation pond in Tottori, Japan was selected for this study. The pond stores runoff from the catchment area and has no inflow from other basins. A siphon tube with a diameter of 20 cm was employed as the EDD for the pond and the discharge performance was evaluated. First, 60-min rainfalls at return periods of different years were estimated. Then, the peak runoff and subsequent arrival time of each year's 60-min rainfall and the discharges from the spillway and siphon were estimated. The water balance of the pond was calculated using the peak runoff as an inflow element, and the discharges from the spillway and the siphon were used as the outflow elements. The results showed that the pond will overflow if a 50-year rainfall event occurs under current conditions; however, it will not overflow when the siphon is employed even if a 60-year rainfall event occurs. Since the siphon discharge was not large enough to pass a flood event greater than 60 years, we developed an EWS that informs villagers living near the pond when the water level of the pond reaches these levels through an alarm lamp and an e-mail. Based on the results of the water balance analysis, the EWS provided information to judge whether villagers should be evacuated or not and the timing of the evacuation in the case of heavy rainfall events if necessary.

Keywords siphon, probability of rainfall, peak runoff, arrival time, water balance

INTRODUCTION

There are 1,094 irrigation ponds in the Tottori Prefecture, Japan as of September 2014. Heavy rainfall increases the risk of floods, which could cause damage to the villages located downstream of the ponds. Two of the possible countermeasures against floods include facility improvements and management of flood preparation plans. The purpose of facility improvements is to construct spillways that will safely pass the flood events, and proper flood management includes the preparation of hazard maps to show evacuation routes as well as the water levels at different places and roads when the flood occurs. The spillways of most irrigation ponds in Japan require repairs to safely pass the 200 year flood event that means the probability of flood occurrence, once per 200 year, which is the design criteria set by the Japanese government (MAFF, 2015). However, due to the large number of ponds and the high repair

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costs, extensive time will be required to repair the spillways of every irrigation ponds. Therefore, we developed a low-cost early warning system (EWS) to reduce the potential risks in the case of floods, as well as a low-cost emergency discharging device (EDD) to help to prevent the floods and mitigate any damages that may be caused. The results of our research will assist with flood management plans in areas that still require spillway repairs.

OBJECTIVE

This study aimed to develop a low-cost EWS to reduce risks in the case of floods as well as a low-cost EDD to help prevent or mitigate the floods. Forecasting or real-time monitoring systems are employed in many EWSs installed at rivers and reservoirs, though they are not often applied to irrigation ponds that typically rely on water level monitoring and warning systems that can send alerts by sirens, lamps, and/or e-mails when the water reaches certain levels. However, these systems do not relay information related to the timing of evacuation to villagers living in the affected areas. Therefore, we developed an EWS that informs villagers living near the pond, through an alarm lamp and e-mail when the water level of the pond reaches certain levels, and on the basis of the results of a water balance analysis, the EWS also provides information during heavy rainfall events to judge whether villagers should be evacuated as well as the timing of evacuation if necessary. The function of an EDD was also quantified in this study to assess the capabilities of the device to prevent or mitigate floods during different rainfall events.

METHODOLOGY

Study Area

The study area selected was the Yutani irrigation pond in Tottori City, Japan. The storage capacity and the catchment area of the pond are 3,800 m^3 and 0.082 km^2, respectively. The pond receives and stores runoff from the catchment area and does not have inflow from other basins. The residential area of the village is located only 200 m downstream from the pond.

Water Balance Analysis

To simulate the water balance and water level of the pond under heavy rainfall, 60-min rainfall events at return periods of 10, 20, 30, 40, 50, 60, 100, and 200 years were estimated using the Iwai method. The hourly rainfall record over a 71-year range (1943–2013) was downloaded from the Japan Meteorological Agency (JMO), and the top 30 rainfall events were used for analysis.

The peak runoff and associated arrival times of the 60-min rainfall event during each year were estimated using the Rational equation and the values were used to simultaneously solve both the Talbot (Eq.1) and Kadoya–Fukushima formulas (Eqs.2 and 3), respectively:

$$I = \frac{a}{t+b} \qquad \text{Eq. 1}$$

$$t_p = C \cdot A^{0.22} \cdot r_e^{-0.35} \qquad \text{Eq. 2}$$

$$r_e = f_p \cdot I \qquad \text{Eq. 3}$$

where I is the rainfall intensity (mm/h), t is the duration of rainfall (min), a and b are the constant parameters related to the meteorological conditions, t_p is the peak flow arrival time (min), C is the parameter related to the land use conditions, A is the catchment area (km^2), r_e is the average effective rainfall intensity (mm/h), and f_p is the peak runoff coefficient.

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The Rational equation for determining the peak discharge from the catchment area and average effective rainfall intensity is expressed as follows:

$$Q = \frac{1}{3.6} \cdot r_e \cdot A \qquad \text{Eq. 4}$$

where Q is the peak runoff (m^3/s). The discharges from the spillway and the emergency discharging device (siphon) were estimated using the hydraulic formula as expressed in Eqs. 4 and 5. The siphon tube was assumed to be 20 cm in inner diameter.

The discharge from the spillway was calculated using rectangular weir or orifice formulas according to the water level. The EDD comprises a siphon tube that was 20 cm in diameter. Therefore, the average velocity of the siphon tube was estimated in consideration of all head losses owing to parameters such as friction and the curve of the tube. The formulas used in the calculation are expressed in Eqs. 5 and 6:

$$Q_s = C_s \cdot b \cdot H^{\frac{3}{2}} \qquad \text{(if the water level is below 0.54 m)} \qquad \text{Eq. 5}$$

$$\text{Qs} = C_0 \cdot b \cdot \sqrt{2g(H_2^{1.5} - (H_2 - H_1)^{1.5})} \qquad \text{(if the water level is over 0.54 m)} \qquad \text{Eq. 6}$$

where Q_s is the discharge from the spillway, C_s and C_o are the discharge coefficients for the rectangular weir or orifice condition, respectively, g is the gravity acceleration (m/s^2), b is the width of the spillway (m), H is the water level of the spillway (m), H_1 is the height from the water surface to the top of the spillway (m), and H_2 is the height from the water surface to the bottom of the spillway (m).

The water balance and rate of increase of the water level of the pond were calculated using the peak runoff as the inflow element and the discharges from the spillway and the siphon as the outflow elements on a secondary basis. Due to the assumption of short and heavy rainfall, evaporation and infiltration from the pond were ignored. The necessary information to create the height–volume curve of the pond was surveyed. The function of EDD was evaluated and the alert and warning water level of the EWS was set on the basis of the results of the simulation.

RESULTS AND DISCUSSION

Estimated Rainfall and the Peak Discharge

The 60-min rainfalls at different return periods; the arrival time; the effective rainfall intensity; and the peak runoff discharge, are shown in Table 1. To meet the design criteria set by the government, the 200-year rainfall intensity was estimated to be 85.4 mm/h, and the arrival time of the peak runoff was estimated to be 34.5 min. The pond was assumed to have a spillway capable of passing discharges at rates >2.10 m^3/s.

Table 1 Estimated rainfall intensity and the peak runoff

Return period (y)	Rainfall intensity (mm/h)	Arrival time (min)	Effective rainfall intensity (mm/h)	Peak runoff (m^3/s)
10	56.3	41.5	53.9	1.24
20	62.5	39.6	61.5	1.42
30	66.2	38.6	66.2	1.53
50	71.1	37.4	72.4	1.67
100	78.0	35.9	81.4	1.88
200	85.4	34.5	91.1	2.10

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Function of the Emergency Discharging Device

The water levels of the pond according to the different years of rainfall were simulated based on the water balance discharge calculated on a secondary basis. Figure 1 shows the peak water level at different years of rainfall with and without the EDD. As shown in the figure, the pond was not predicted to overflow when the 30-year rainfall event occurred, regardless of the presence or absence of the EDD. However, the pond was predicted to overflow during the 50-year rainfall event without the presence of the EDD, while it was not predicted to overflow until a greater-than- 60-year rainfall event occurred when the EDD was present.

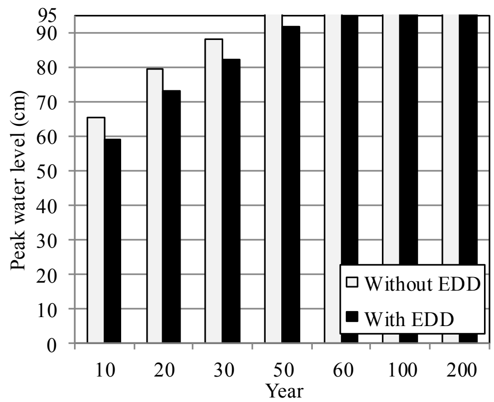

Fig. 1 Peak water levels for different years of rainfall events, where 95 cm refers to the top of the dike

Figure 2 shows a comparison of the discharges from the spillway and EDD. The EDD was observed to discharge more than the spillway during peak runoff, and when the water level reached the top of the spillway at 54 cm, the discharge from the spillway exceeded the EDD. When the maximum discharge occurred, the EDD contributed to approximately 20% of the total discharge. The result of the water balance simulation indicated the requirement for an EWS to alert the villagers to be evacuated when a greater-than-60-year rainfall event occurs.

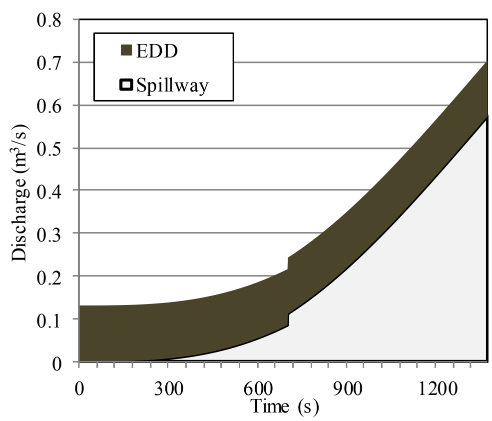

Fig. 2 Comparison of the discharges simulated for the spillway and the EDD

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Setting Alert and Warning Water Level of the EWS

The EWS has two water sensors at different water levels. The sensor set at the lower water level is considered as the alert water level to indicate the villagers to start preparing for evacuation, while the other sensor set to a higher water level is considered as the warning water level to indicate the timing of the evacuation. Based on the evacuation route found on the hazard map made by the villagers and the Tottori Prefectural Federation of Land Improvement Association (2014), the time to evacuate from the houses to the designated safe places is estimated to be 10 min, with an additional 5 min assumed to be necessary to prepare for the evacuation. Therefore, the warning water level can be defined as the water level that is measured 10 min before the flood occurs (95 cm), and the alert water level can be defined as the water level that is measured 5 min before the water level reaches the warning level. As explained above, the pond will overflow when a greater- than-60-year rainfall event occurs. If the time for the water level to rise from alert to warning is less than 5 min during a greater-than-60-year rainfall event, then it should take longer than 5 min for the water level to rise from alert to warning during a less-than-60-year rainfall event. This means that the villagers can judge whether they need to be evacuated by the time it takes the water level to rise from the alert to the warning levels. The concept of setting the warning and alert water levels is illustrated in Fig. 3.

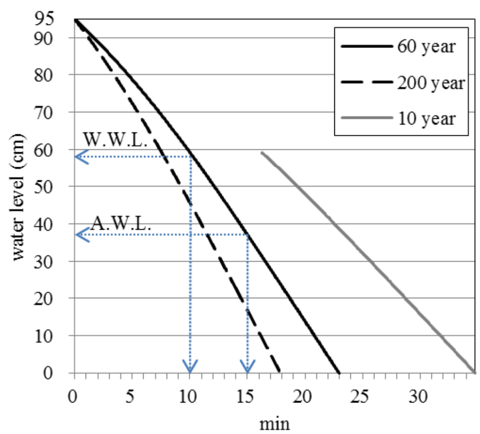

Fig. 3 Concept of setting the warning and alert water levels, where A.W.L. indicates the alert water level, and W.W.L indicates the warning water level

Table 2 Time required for the water to reach between two different levels

Water level	30 cm	40 cm	54 cm	60 cm	95 cm
20 cm	2 min 8 s	4 min 19 s	7 min 27 s	8 min 52 s	18 min 40 s
30 cm	-	2 min 11 s	5 min 19 s	6 min 44 s	16 min 32 s
40 cm	-	-	3 min 8 s	4 min 33 s	14 min 21 s
54 cm	-	-	-	1 min 25 s	11 min 13 s
60 cm	-	-	-	-	9 min 48 s

Table 2 shows the time for the water level to reach 20, 30, 40, 54, 60, and 95 cm under a 60-year rainfall event. The distance of 54 cm was selected instead of 50 cm because the top of the spillway is 54 cm, and this distance makes it easier for people to gauge the water level immediately. From the table, the alert water level should be set lower than 54 cm to obtain more than 10 min for evacuation. Supposing the warning water level is set to 54 cm, the starting water level will be 40 cm to result in a rise to 54 cm in less than 5 min. However, the preparation time for evacuation is only 3 min and is too less for people to prepare for evacuation. Therefore, we set the alert water level to 30 cm. Following

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that, if the time of the water level rise from 30 to 54 cm is less than 6 min, we can judge if evacuation needs to occur.

Installation of the EDD and the EWS

The EWS and EDD were installed at the studied irrigation pond (see Fig. 4). The opening and closing of the 20-cm diameter siphon tube (KanaLine N. S., Kanaflex Co., ltd.) is controlled by an electric bulb (Butterfly Valve Electric Actuated Type T-57, Asahi Organic Chemicals Industry Co., ltd.). The EWS was settled at the dike and sends e-mails to registered people such as villagers, local government officers, and university officials when the water level rises up to the alert and warning water levels and also informs the villagers via an alarm lamp.

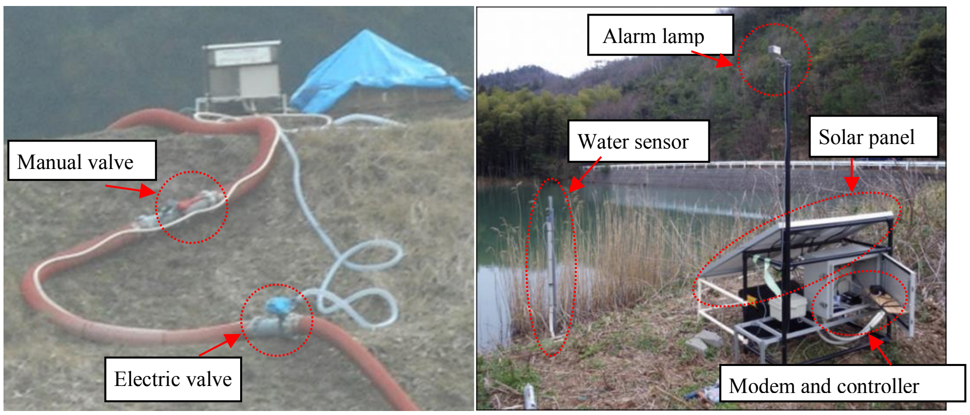

Fig. 4 Photographs of the EDD (left) and the EWS (right)

CONCLUSION

An EWS and EDD were developed to reduce the risk in case of floods and to prevent or mitigate the floods at an irrigation pond that did not have a sufficiently large spillway to safely pass a discharge caused by heavy rainfall. The developed EDD could not satisfy the criteria designed by the government but could prevent against floods caused by less-than-60-year rainfall events. The EDD enhanced the drainage function by at least 20% during flood conditions. The previous EWS had just informed the relevant people and agencies when the water level reached a certain level, but the newly developed EWS presented in this work is a type of epoch-making device in terms of informing the timing of potential evacuations. Our results also suggested that multiple countermeasures such as a combination of EDD, EWS, and hazard maps are required to prevent floods and mitigate flood damage to people.

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